VARIABILITY REDUCTION
IN THE UNITED STATES AIR FORCE:
DEVELOPMENT OF A HANDBOOK

THESIS

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THESIS

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of the Air Force Institute of Technology

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Master of Science in Logistics Management

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Preface

Initial research indicated there was a general lack of knowledge about Variability Reduction and its role in the United States Air Force. The focus of this research therefore, was to develop a Variability Reduction Process Handbook to inform Air Force managers of the concepts and methodologies involved in Variability Reduction.

This research effort would not have been successful without the support and assistance of others. I would like to express my sincere appreciation to my thesis advisor, Lt Col Robert D. Materna, for his patience, guidance, and assistance throughout the thesis process. Special thanks are extended to Lt Col Richard I. Moore whose valuable assistance as reader was instrumental in validating the handbook. Additionally, I would like to acknowledge Lt Col Phillip E. Miller and Dr. David K. Vaughan for their helpful inputs.

Furthermore, I wish to recognize Capt Bruce A. Johnson at HQ USAF, LE-RD, at the Pentagon, for his valuable assistance especially during the validation phase of the handbook.

Lastly, I would like to thank my wife, Janet, and our two children, Allan and Kathy, for their infinite patience and understanding during the last year. Words cannot express my everlasting appreciation for their love and support.

Vance A. Daunheimer

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Abstract

The focus of this study is on Variability Reduction. Specifically, this thesis reviews Air Force policy regarding Variability Reduction, examines Variability Reduction's role in the Department of Defense's Total Quality Management (TQM) initiative including the United States Air Force Reliability and Maintainability 2000 (USAF R&M 2000) Process, and addresses several Variability Reduction methods. The primary objective of the research was to produce a Variability Reduction Process Handbook explaining several of the concepts involved in Variability Reduction, thus providing Air Force managers a better understanding of Variability Reduction methodologies. Additionally, the handbook emphasizes the importance of implementing this aspect of quality.

Variability Reduction methods can be applied to selected phases within a system's life cycle and are essential to integrating two seemingly incompatible goals--fielding highly reliable and maintainable systems while decreasing development time and reducing production and operational costs. Variability Reduction stresses uniformity around a target value rather than conformance to specification limits. Furthermore, robust designs make products insensitive to various sources of product variation, thus improving performance and enhancing reliability.

VARIABILITY REDUCTION

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I. Introduction

Overview

In 1987, the Reliability and Maintainability (R&M) 2000 Variability Reduction Process (VRP) was established as part of the Total Quality Management (TQM) initiative to enhance quality, reliability, and maintainability of Air Force systems while reducing costs and development time (DoD 5000.51-G, 1989:74). In Japan, the term "VRP" has established itself as a concept synonymous with manufacturing excellence producing products insensitive to physical and functional variation caused through manufacturing, the environment, and usage. Variability Reduction emphasizes optimum performance values in lieu of specification limits. Thus, VRP attempts to eliminate performance and product variations caused by design and manufacturing processes. A 1987 article in Quality Progress, "The Power of Taguchi Methods," states:

> Employees and suppliers must begin to think of the quality of products and services not only in the customer sense, but relative to the quality of the processes that produce them. In this regard, we should focus on methods to reduce the variability of process output, not just meeting specifications. (Sullivan, 1987a:76)

VRP is a means to improve quality, reliability, and maintainability of Air Force systems at reduced costs by eliminating performance variations in products caused either by design or manufacturing processes. As such, VRP is a useful tool applicable throughout a system's life cycle up to disposal. As represented in Figure 1, VRP techniques are best employed in the development, design, and production stages. These stages are perhaps the most important stages from an acquisition point of view in a systems life cycle as "studies have shown that, by the end of full scale development, up to 80-95% of the decisions which determine total life cycle costs have been made" (Materna and Andrews, 1988:5-2).

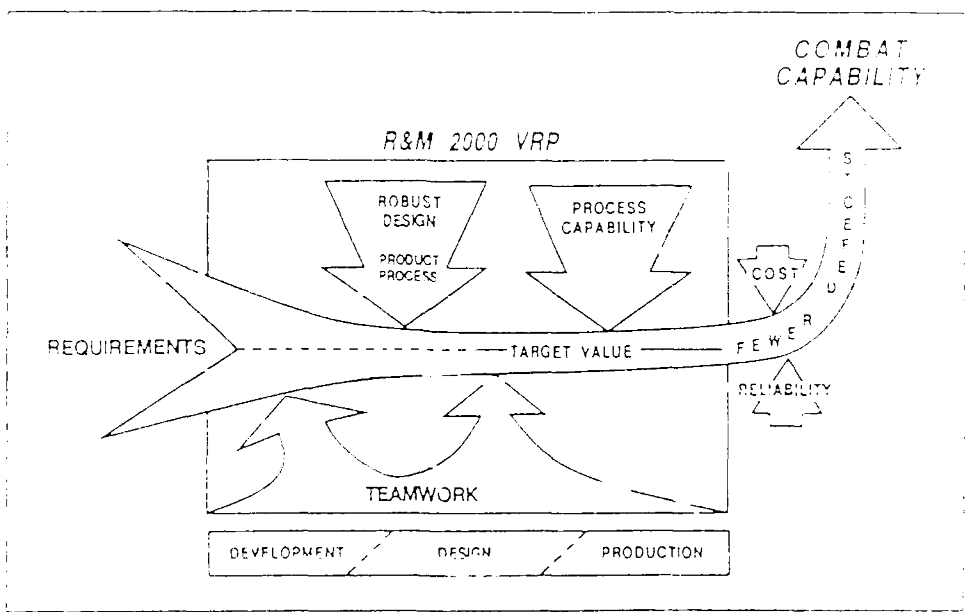


Figure 1

USAF R&M 2000 VRP (Source: HQ USAF/LE-RD, 1988:5)

As illustrated in Figure 2, using VRP in this "window of opportunity" can significantly impact the cost of a new system as well as enhancing performance characteristics and R&M. Whereas VRP is useful in developing totally new systems, it also has applications in the design and manufacturing phases during modifications and upgrades of existing systems and applies to post production support and repair activities of all Air Force systems (Hatch, 1988).

Reducing variability around a target (or best) value shortens product development time, reduces design and redesign costs, and eliminates waste in manufacturing operations ultimately producing a robust product--a product that is insensitive to functional variation.

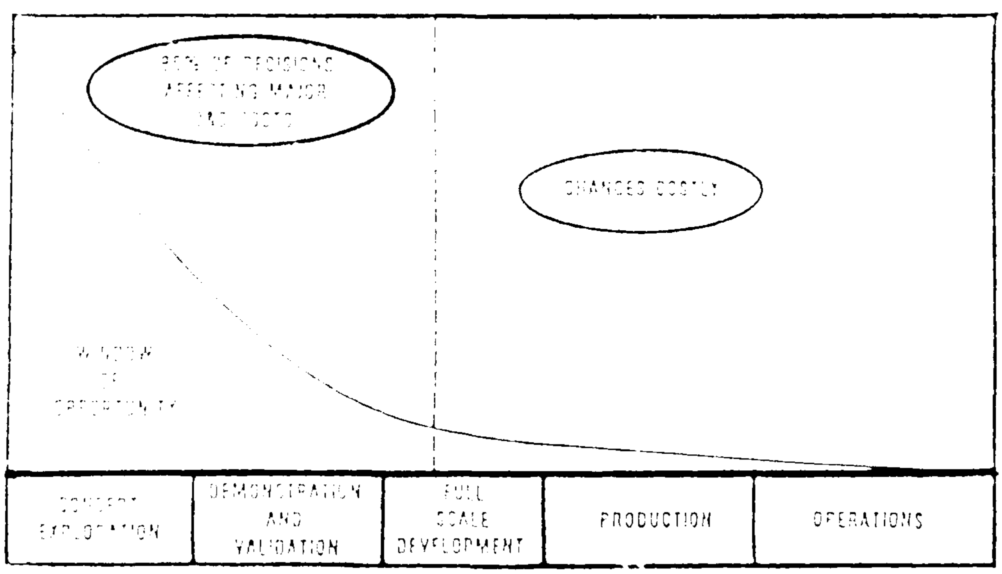


Figure 2

Window of Opportunity (Source: Materna and Andrews, 1988:5-3)

The benefit of applying VRP is shown in Figure 3 by the F100 turbine blade grinding process. Prior to VRP, the distribution of critical part characteristics exceeded the upper specification limit of 80.93 resulting in a rework rate of 3.2 percent (VRP Guidebook, 1989:11). After applying VRP techniques to remove the causes of variation, manufacturing variability was reduced and no rework was required. Thus, VRP eliminated wasting money to rework scrap in the "hidden factory" and the necessity of having to do it again a second time to make it right.

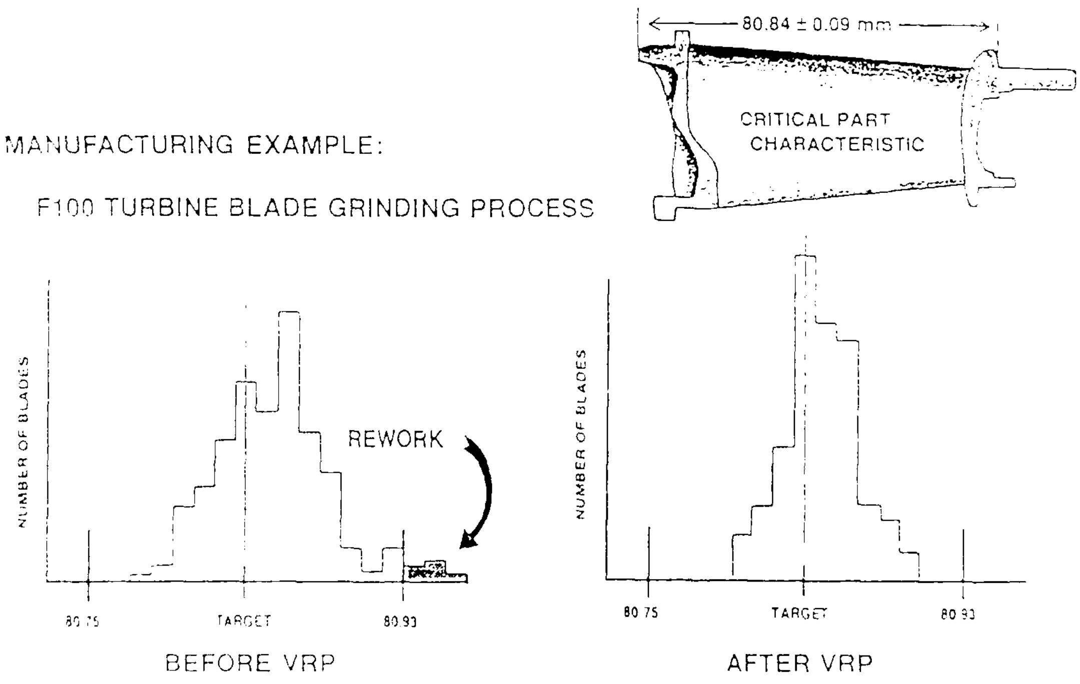
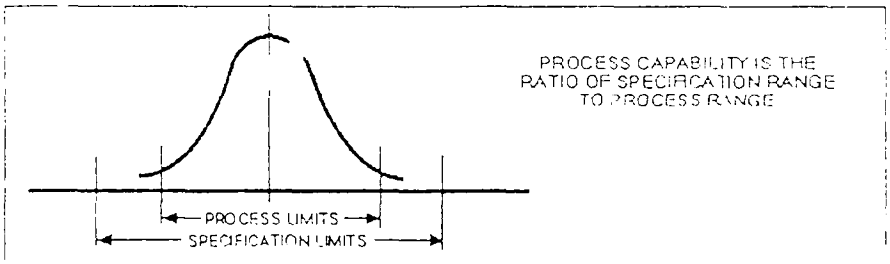


Figure 3

Applying VRP (Source: VRP Guidebook, 1989:12a)

Variability Reduction is a building block in the USAF Reliability and Maintainability 2000 Process and an important element within the Total Quality Management initiative. VRP integrates Statistical Process Control (SPC), or on-line variability reduction, to reduce variability in manufacturing and assembly processes. Production workers monitor their own work to control processes and collect data which is statistically analyzed to identify special and common causes of variability. Once identified, workers can eliminate special causes of variability so as to maintain a stable process establishing a state of statistical control. This stable production process produces increasingly more uniform, defect free products which have yielded less than 1 part-per-billion defective as shown in Figure 4 (Hull, 1988:4).



PROCESS CAPABILITY (Cp)	PPM DEFECTIVE
0.60	71,800
0.90	6,900
1.00	2,700
1.33	66
1.67	<1
4.50	<<1 PPB

Figure 4

Process Capability (Hull, 1988:4)

Off-line Variability Reduction methods performed at the product and process design stages are quality and cost control measures contrived to improve product manufacturability, reliability, and maintainability while reducing product development time and life cycle costs. Introducing countermeasures to reduce controllable sources of variability can optimally be achieved in the product design phase as displayed in Figure 5 (Kacker, 1987:67).

Product development stages where countermeasures against various sources of variation can be designed into the product.

Product Development Stages	Sources of variation		
	Environmental Variables	Product Deterioration	Manufacturing Variations'
Product Design	YES	YES	YES
Process Design	NO	NO	YES
Manufacturing	NO	NO	YES

Figure 5

Countermeasures against Sources of Variation (Kacker, 1987:67)

Parameter design is one such off-line Variability Reduction method. The objective of parameter design is to identify product design characteristics that render product performance less sensitive to the effects of environmental variables, deterioration, and manufacturing variations. Parameter design is a cost-effective method to improve a product's field performance by reducing the effects of environmental variables, product deterioration, and manufacturing imperfections. Thus, parameter design provides robustness in product design, reducing sources of variation, and improving field performance (Kackar, 1985:176).

The importance of parameter design can be illustrated by examining the 1980 U.S. attempt to rescue the hostages in Iran. The mission failed because the helicopters participating in the rescue attempt encountered a dust storm. The dust ultimately destroyed the bearings and clogged the engines of the helicopters. If the helicopters had been robustly designed to withstand severe dust storms, the outcome of the mission could have been different. It is a common consensus that the field performance of a product is affected by environmental variables (as well as human variations in operation), product deterioration, and manufacturing imperfections. If the helicopters had been robustly designed, environmental factors (the dust) would not have caused product deterioration (failing helicopter engines) and mission outcome could have been different. This

example illustrates the significance of why weapon systems must be designed and produced robustly--insensitive to functional and environmental variation. Ultimately, the success or failure of a mission **may** depend on it.

<u>Background</u>

Success of the United States defense posture depends on countering a numerically superior enemy by employing qualitatively superior weapon systems--weapon systems that **must sustain operational performance over time**. Highly reliable and maintainable systems are critical variables in the equation of successfully engaging and defeating a numerically superior enemy. With a clear focus on maximizing resources, key concerns are optimizing quality and enhancing reliability and maintainability. Consequently, the effective and efficient use of resources along the path from the "drawing board" to the "flight line" has never been more critical. Variability Reduction is a viable tool for improving the quality, reliability, and maintainability of Air Force systems. Thus, it is imperative that Air Force managers understand the principles behind this concept.

<u>Policy Letter #6: R&M 2000 Variability Reduction</u> establishes Air Force policy regarding Variability Reduction to improve the quality, reliability, and maintainability of Air Force systems at reduced costs. This policy letter directs acquisition commands to derive maximum benefit from

the Variability Reduction Process by achieving the following objectives by 1993:

a. Ensure validated user requirements are the basis for all actions.

b. Develop new systems or modifications/upgrades to existing systems simultaneously with their production processes. Ensure that the product and the process are as fully integrated as possible to meet user requirements at the lowest possible cost. Evaluate progress in this area during each design review.

c. Reduce performance variations in both the product and the manufacturing process until reaching the most cost-effective level. Assess cost effectiveness using the monetary loss function.

d. Conduct training in variability reduction concepts and techniques for personnel working in acquisition and repair activities. (Hatch, 1988)

This policy applies to acquisition and post-production support of all Air Force systems, subsystems, and equipment. The purpose of the Variability Reduction Program is to improve combat capability by producing more reliable, maintainable, and defect-free weapon systems. Because the products manufactured contain fewer defects, warranty and rework costs are reduced decreasing acquisition time and total life cycle costs.

Problem Statement

Specific guidelines for achieving Variability Reduction do not exist. Exploratory research conducted in the form of semi-structured phone interviews with personnel at various AFLC divisions and branches at Wright-Patterson AFB suggested the absence of a thorough understanding of the processes

involved in Variability Reduction. Another semi-structured phone interview with HQ USAF/LE-RD at the Pentagon confirmed these findings as HQ USAF/LE-RD expressed concern about the lack of basic understanding regarding Variability Reduction methodologies. Therefore, the purpose of this thesis was to produce a handbook explaining Variability Reduction concepts and Total Quality Management techniques that could be used by Air Force managers to reduce variability.

Purpose of the Handbook

The purpose of the handbook is to present Variability Reduction concepts in an understandable manner to expose Air Force managers to methodologies used in Variability Reduction. By applying Variability Reduction techniques to selected phases in a system's life cycle, Air Force personnel will be better able to manage the development, production, and support of highly reliable and maintainable, combat capable systems while decreasing development time and reducing production and operational costs as well. Improved management through the effective use of Variability Reduction methodologies could be transformed into substantial savings in the form of cost effective systems possessing enhanced R&M.

Research Question

The exploratory research indicated that many Air Force managers today do not thoroughly understand how to achieve

the Variability Reduction objectives set forth in Policy Letter #6: R&M 2000 Variability Reduction. This exploratory research conceived the basis of the research question "What Total Quality Management methods are most effective in achieving Variability Reduction policy objectives?"

Investigative Questions

To effectively address the aforementioned research question, the following investigative questions were developed:

1. What official guidelines and directives exist within the USAF pertaining to VRP?
2. What Variability Reduction methodologies should be covered in a Variability Reduction Process Handbook?
3. How can the effects of VRP be measured?

Scope and Limitations

The purpose of this thesis was to produce a Variability Reduction Process Handbook. All Air Force personnel working any phase of system acquisition or modification should understand VRP principles and be able to apply the concepts presented in the handbook. VRP is a means to improve quality, reliability, and maintainability of Air Force systems at reduced costs by eliminating performance variations in products caused either by design or manufacturing processes. As such, VRP has a broad range of application throughout the Air Force, especially within the

acquisition commands. Although VRP is useful in developing totally new systems, it also has applications in the design and manufacturing phases during modifications and upgrades of existing systems.

Although this study attempted to consider all possible methods available for Variability Reduction, time constraints dictated the necessity of focusing on a select few. The methodologies selected for incorporation into the handbook were the most effective for accomplishing Variability Reduction according to the inputs obtained from the exploratory research, the USAF R&M 2000 Process, recommendations from HQ USAF/LE-RD, and the writings of other "Quality" experts such as Taguchi, Juran, Feigenbaum, Kackar, and L.P. Sullivan. These methodologies included Quality Function Deployment, Statistical Process Control, Troubleshooting Techniques, and Taguchi Methods.

Organization of the Thesis

This chapter provided background information on the Variability Reduction Process, stated the problem, addressed the purpose of the handbook, listed the research and investigative questions, and covered the scope and limitations of the research. Chapter II explains the methodology followed in developing the Variability Reduction Process Handbook including a literature review of Variability Reduction methodologies and the role of VRP in TQM and the R&M 2000 Process. Chapter III presents the findings for the

investigative questions while Chapter IV offers conclusions, discusses the implications of VRP for the Air Force, and provides recommendations for future research.

II. Methodology

Overview

The purpose of the Variability Reduction Process Handbook is to provide a source document to enhance the understanding of the methodologies involved in Variability Reduction. Reducing variability around a target (or best) value shortens product development time, reduces design and redesign costs, and eliminates waste in manufacturing operations ultimately producing a robust product--a product that is insensitive to functional variation. This in turn increases combat capability by producing more reliable and maintainable systems while simultaneously reducing acquisition time and costs.

The handbook provides Air Force managers a consolidated source of information pertaining to the Variability Reduction Process. The handbook addresses proven management methods that, when properly applied, contribute to Variability Reduction. The purpose of the handbook is **not** to produce expert statisticians, but to present Variability Reduction concepts in an understandable manner to expose Air Force managers to methodologies used in Variability Reduction.

Moreover, understanding Variability Reduction methodologies is essential towards achieving the policy objectives established by Policy Letter #6. Therefore, the initial focus of the research process was to investigate

established Variability Reduction methodologies and examine the role of Variability Reduction as part of the Total Quality Management initiative and R&M 2000 Process.

Research Process

Previously listed investigative questions were developed to answer the research question "What Total Quality Management methods are effective in achieving Variability Reduction policy objectives?" Therefore, research efforts initially focused on identifying proven quality management techniques which were effective in reducing variability. An exploratory review of the literature published in quality oriented periodicals, government documents, and books written by renown Quality experts such as Genichi Taguchi, W. Edwards Deming, J. M. Juran, Lawrence P. Sullivan, Raghu Kackar, and Armand Feigenbaum was initially conducted.

This preliminary literature review was combined with several semi-structured phone and personal interviews with Quality specialists at HQ USAF/LE-RD at the Pentagon and Wright-Patterson AFB to establish a baseline of quality management techniques useful in Variability Reduction. These interviews, semi-structured in design, were developed to provide further insight into Variability Reduction methods. The semi-structured nature of the interview afforded the expert the opportunity to freely offer unsolicited information pertaining to other Variability Reduction techniques and to elaborate upon the specific advantages and

disadvantages of each. This supplemental information was often a valuable source of information providing pragmatic views into particular methods.

The three primary techniques most often identified during this initial investigation as effective quality management methods in reducing variability were Quality Function Deployment, Statistical Process Control, and the Loss Function. Furthermore, these techniques were also referenced as the preferred practices recommended in the USAF R&M 2000 Process for achieving Variability Reduction. The research effort then focused on collecting, organizing, and analyzing data on these methodologies as well as examining the philosophies of Taguchi, Crosby, Juran, and others.

Review of the Literature

The purpose of this segment is to review the literature associated with the Variability Reduction Process and examine its role in the Total Quality Management initiative and R&M 2000 Process. The literature review consists of three sections. The first section provides a working definition for Total Quality Management. The second section discusses the Variability Reduction Process--what it is, what drives it, why it was implemented, and what it is supposed to accomplish. The third and perhaps most important section of this literature review describes proven "Quality" management techniques, that when applied, contribute to Variability Reduction.

Total Quality Management. The Total Quality Management initiative is the driving force behind the Variability Reduction Process. TQM is a managerial philosophy directed at establishing continuous improvement in all DoD activities (DoD 5000.51-G, 1989:1). As depicted in Figure 6, VRP is a shared element of both TQM and the R&M 2000 Process.

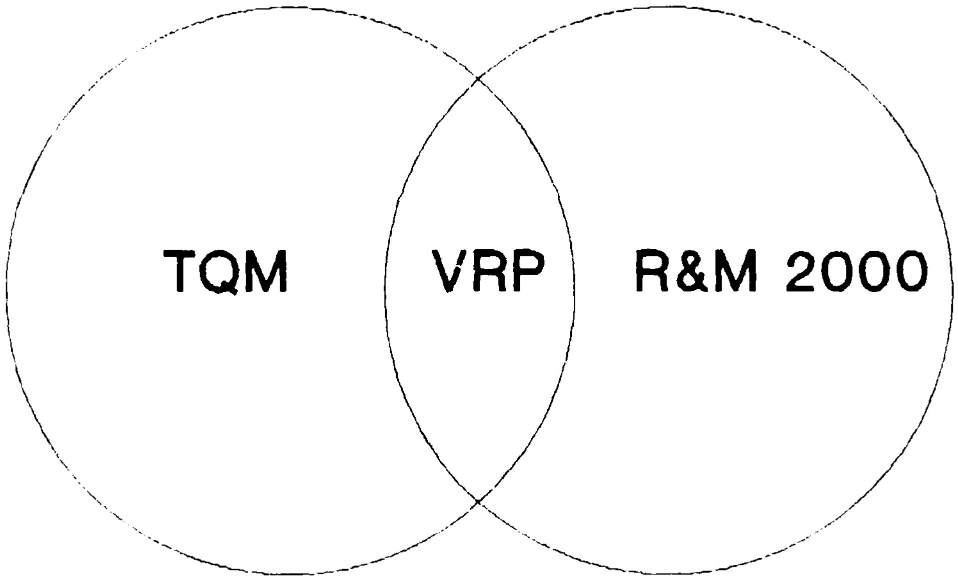


Figure 6

Relationship Between TQM, R&M 2000, and VRP

The TQM strategy emphasizes doing the right thing, right the first time, on time, all the time while continuously striving for improvement and always satisfying the customer.

DoD 5000.51-G provides the following definition for TQM:

> TQM consists of continuous process improvement activities involving everyone in an organization--managers and workers--in a totally integrated effort toward improving performance at every level. This improved performance is directed toward satisfying such cross-functional goals as quality, cost, schedule, mission need, and suitability. TQM integrates fundamental management techniques, existing improvement efforts, and technical tools under a disciplined approach focused on continuous process improvement. The activities are ultimately focused on increased customer/user satisfaction. (DoD 5000.51-G, 1989:1)

Total. In regard to quality, total is defined as a systematic approach of gathering and analyzing data and then using this information to produce an intended result while ensuring all necessary and applicable information is considered and integrated effectively towards the intended result (Caplan, 1980:Ch1). Essentially, quality management is managing to assure total company productivity--to make the scientist, the engineer, and the customer a **sum** rather than a **difference** (Feigenbaum, 1983:4). Ultimate levels of quality and productivity will be achieved only by people who know how to work together as a team (Tribus:199).

Quality. The issue of Quality is essential for survival in today's world--not only in the business arena but also within the DoD. Deservedly, it has received considerable attention as much has been written about quality. In fact, there are almost as many different

definitions for quality as there are experts writing about it. However, the basic message behind the differing quality definitions is essentially the same--to satisfy the customer's needs.

Quality is based upon the customer's actual experience with the product or service, measured against his or her particular requirements--stated or unstated, conscious or merely sensed, to the extent in which the product and service in use meets the expectations of the customer (Feigenbaum, 1983:7). More simply put, "quality means fitness for use" (Juran, 1980:1). Taguchi views quality in terms of "loss to society." Taguchi looks at quality not in terms of value added but in terms of "the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions" (Taguchi, 1985:7). The American Society for Quality Control defines quality as "the totality of features and characteristics of a product or service that bear on its ability to satisfy (a user's) given needs." There is no occupation anywhere in which satisfying the customer's needs is more critical than in the defense industry where the stakes are substantially higher than mere profit and loss (Rittenhouse, 1986:12).

Historically, American management has viewed quality from the perspective that quality **costs** money. This differs from Japanese philosophy advocating quality **makes** money. Japanese implementation of concepts such as Statistical

Quality Control and Total Quality Control were part of a program to establish extremely high standards for products and people. Moreover, Japanese managers conveyed their commitment to quality by providing opportunities for their employees to study these quality techniques during working hours. Japanese commitment to quality through continuous improvement by constantly striving to provide customers with products that not only met requirements but exceeded them is a major reason for Japanese success in the marketplace (Harrington, 1987:Ch1).

Measuring Quality. Kaoru Ishikawa defines Total Quality Control (TQC) as "the system for integrating quality technologies into various functional departments (i.e. engineering, production, sales, and service) to achieve customer satisfaction" (Ishikawa, 1983).

In Japan, TQC embodies three stages of quality. The first stage is a product oriented approach of measuring quality through inspection after production. Statistical sampling plans, operating characteristic curves, and tables for acceptable quality levels (AQL) are developed and used to evaluate quality. The second stage is process oriented. During this stage, quality control during production is based primarily on Statistical Process Control. Finally, the third stage is a systems oriented approach to quality assurance. In this stage, the "Voice of the Customer" is deployed horizontally within the company emphasizing horizontal

interaction between all departments while preserving a constant focus on quality control (Sullivan, 1986a:78-81).

Many U.S. textbooks discussing TQC emphasize quality control technology based on the traditional definition of quality as conformance to requirement (i.e. specification, customer expectation, etc.). From this perspective, the cost of quality refers to the cost of conformance while managing and correcting any nonconformance. Internal company costs include prevention, appraisal, failure, and external costs due to customer problems. In comparison, Japanese companies have taken quality control technology a step farther stressing the humanistic aspect of quality by emphasizing the "Voice of the Customer" throughout the company and considering the importance of employee contribution towards continued quality improvement at lower costs. As per Japanese philosophy, cost is viewed in terms of loss to society and is determined by design cost, efficiencies in manufacturing, assembly, sales, service, customer ownership, and contribution to society (Sullivan, 1986a:78).

An essential step in achieving quality is knowing how to measure it. Crosby states:

> Quality is free, but no one is ever going to know it, if there isn't some sort of agreed-on system of measurement. Quality has always suffered from the lack of an obvious method of measurement. (Crosby, 1980:102-103)

The essence of Crosby's message is that quality must be quantified to be measured. Crosby contends that the cost of

quality can be calculated by examining costs like rework, scrap, warranty, inspection, and test. To make the total calculation more meaningful, it must be related to a significant base. Therefore, the purpose of the numbers is to communicate the importance of the concept. Crosby further suggests three categories for measuring the cost of quality. These categories are prevention costs, appraisal costs, and failure costs (Crosby, 1980:103-105).

Prevention costs are costs incurred for off-line activities to prevent defects in design and development, purchasing, labor, or any other matter involved in beginning or creating a product or service. Prevention costs include design reviews, product qualification, drawing checking, engineering quality orientation, supplier evaluations, specification review, acceptance planning, and quality audits.

Appraisal costs are the costs required to inspect, test, and evaluate the output--to determine whether produced hardware, software, or services conform to their requirements. These requirements include all engineering documents and information related to procedures and processes as well as customer specifications. On-line activities such as production specification conformance analysis is an example of an appraisal cost. Other examples of appraisal costs include receiving inspection and test, prototype

inspection and test, product acceptance, and status measurement and reporting.

Failure costs are costs connected to items not conforming to specifications or performing to requirements. Included in failure costs are the evaluation, disposition, and consumer relations affected by the failure as well as the materials and labor required to fix the failure. Failure costs include costs associated with redesign, engineering change orders, corrective action costs, rework, scrap, warranty, and service (Crosby, 1980:105-106).

Management. Management is basically the process through which we plan, organize, coordinate, direct, and control activities. Blanchard defines the major functions of management to include:

> the definition and establishment of objectives, organizing and implementing the tasks necessary to achieve the desired results, and directing and controlling activities to ensure that these results are ultimately attained. (Blanchard, 1986:348)

Gitlow states the purpose of management is to lead an organization in the direction of never-ending and continuous improvement (Gitlow, 1989:533). There is perhaps no more important realm of human activity than managing because the basic task of all managers at any level in any type of enterprise is to design and maintain an environment in which individuals, working in groups, can accomplish preselected missions and objectives. In other words, "managers are charged with the responsibility of taking actions that will

make it possible for individuals to make their best contributions to group objectives" (Koontz, O'Donnell, and Weihrich, 1980:6).

R&M 2000 Process. The R&M 2000 Process is a subset of TQM (DoD 5000.51-G, 1989:74). R&M 2000 operational goals advocate, as a corollary to performance, increased combat capability, decreased vulnerability of the combat support structure, decreased mobility requirements per unit, decreased manpower requirements per unit of output, and decreased costs. "Achieving these goals will reduce the life cycle costs of systems, reduce systems' dependency on spare parts, require fewer combat support personnel, and result in more missions per deployed system" (USAF Fact Sheet, 85-27,1). Enhanced reliability and maintainability in our weapon systems and related support systems will not only increase our combat capability but will save valuable resources as well.

A great deal of emphasis has been placed in the area of Reliability and Maintainability over the past few years--and justifiably so. After all, there's no advantage in possessing a technologically superior weapon system if it's unable to accomplish its mission due to some R&M deficiency. Both the Air Force and defense industry must be committed to producing highly reliable and maintainable systems to meet mission and cost requirements not only for today, but into the year 2000 and beyond (Guzzi, 1987:314).

Reliability and Maintainability. The Air Force developed the R&M 2000 Process to meet this commitment of producing highly reliable and maintainable systems by establishing an "R&M Strategy and Focus" throughout the Air Force and defense industry (Guzzi, 1987:315). This commitment to R&M was emphasized in a 1986 Action Memorandum from E.C. Aldridge, Jr., Secretary of the Air Force, and General Larry D. Welch, Chief of Staff. The action memorandum stated:

> At no time in history has the Air Force commitment to R&M been more important. Improved Reliability and Maintainability will be the key to the effectiveness of our new systems and to the effectiveness of current systems. (Aldridge and Welch, 1986)

Blanchard defines reliability as "the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions" (Blanchard, 1983:12). Moreover, Blanchard defines maintainability as "the ability of an item to be maintained as it pertains to the ease, accuracy, safety, and economy in the performance of maintenance actions" (Blanchard, 1983:15).

The importance of enhanced reliability can be shown by a study commissioned by ASD/XRS at Wright-Patterson AFB entitled "USAF High Reliability (HI-REL) Fighter Concept Investigation Study." The study identified technologies and design concepts which should be considered in the early phases of aircraft modification or development. The study

compared the war fighting capability of a baseline aircraft and variants of an improved high reliability fighter in a 30 day war simulation. War fighting capability was predicted by analytical models in terms of "targets killed per operating day." Figure 7 illustrates the results of the model.

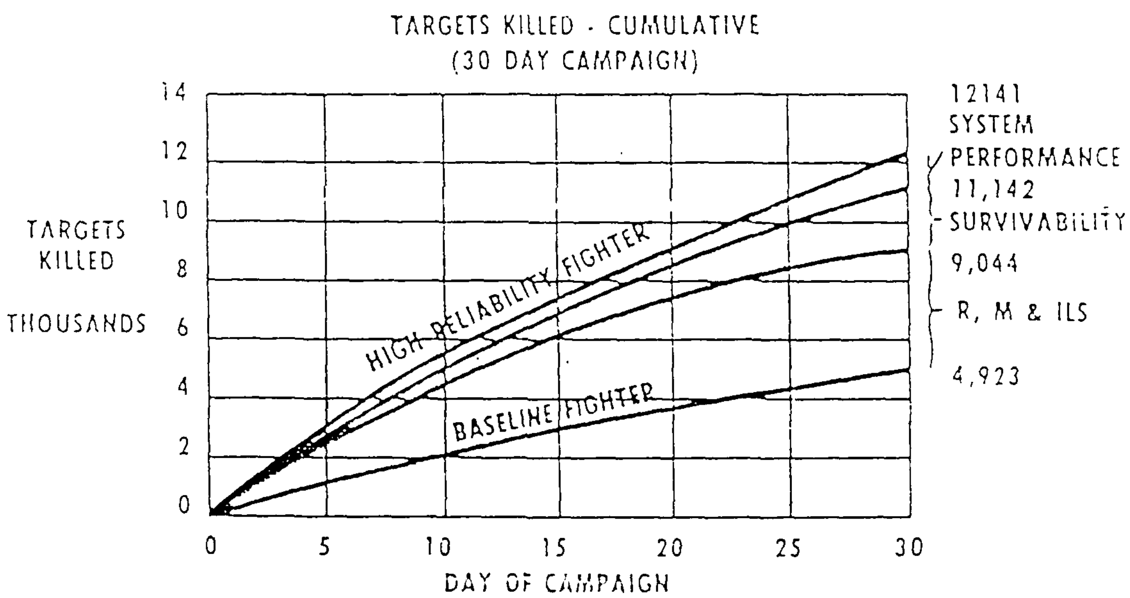


Figure 7

HI-REL Model Results (Source: ASD/XRS, 1989:1-2)

The bottom curve represents the baseline fighter. The curve above the bottom curve shows an increase in targets killed due to improved sortie generation rates only. Additionally, improved R&M means better mission reliability with critical systems failing less often during critical phases of the mission. This translates into improved survivability and more targets killed as represented by the top curves in the figure (AFOLTA, 1989:1-3).

Preservation. The R&M 2000 principles are the basic tenets of the R&M 2000 Process (R&M 2000 Process:10). The R&M 2000 principle called preservation directs aggressive action be taken to ensure inherent Reliability and Maintainability are preserved during production and sustained in the operational environment. Preservation also advocates that feedback be used to continually improve products and processes. Variability Reduction is one tool for achieving the goals of preservation.

Variability Reduction Process. The R&M 2000 Variability Reduction Process (VRP) is an R&M 2000 building block whose purpose is to improve the R&M of Air Force systems while simultaneously reducing costs. The strategy of VRP is to adopt a modern concept of design and manufacturing excellence within the Air Force and the defense industry virtually eliminating poor design and manufacturing processes that produce unreliable equipment that is both difficult and costly to maintain. The purpose of VRP is to produce a

product that is insensitive to physical and functional variation due to manufacturing, the environment, and operational use. As such, VRP addresses the causes of the problem, not just the symptoms. Reducing variability around a preestablished target value diminishes product development time, reduces design and redesign costs, and eliminates waste in manufacturing operations, system support and service use (Hull, 1988:4).

The R&M 2000 Process addresses three methods for reducing the variability around the target value. As illustrated in Figure 8, these methods are Quality Function Deployment, Statistical Process Control, and the Loss Function (R&M 2000 Process, 1988:92-94).

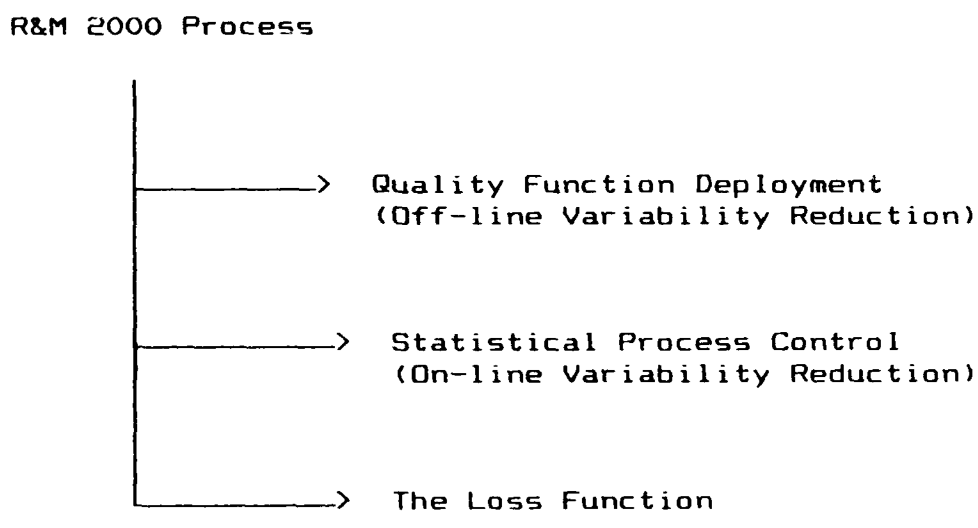


Figure 8

R&M 2000 VRP Techniques

Quality Function Deployment. Quality Function Deployment (QFD) is a methodology developed in Japan for the purpose of reducing time and decreasing costs directly related to new product development while simultaneously improving fitness for use. QFD is a systematic approach for translating the users' requirements into product and process characteristics--translating the "Voice of the Customer" into actionable terms within the design or the process. Within the context of the USAF, the R&M 2000 Process identifies the "Voice of the Customer" as the combat commands' requirements. Therefore, QFD is a technique that identifies customer requirements and provides a discipline to assure that those requirements drive product design and process planning by systematically identifying and exposing necessary considerations requiring attention and improvement (Morrell, 1987:1). As depicted in Figure 9, QFD accomplishes this by translating customer requirements into engineering or design requirements which are then translated into product or part characteristics. These characteristics are, in turn, translated first into process plans and second into specific operations, conditions, or controls. The focus of all these transformations is to assure the customer's requirements (i.e. Voice of the Customer) are considered throughout the entire process and ultimately used in designing the final product (Schubert, 1988:132).

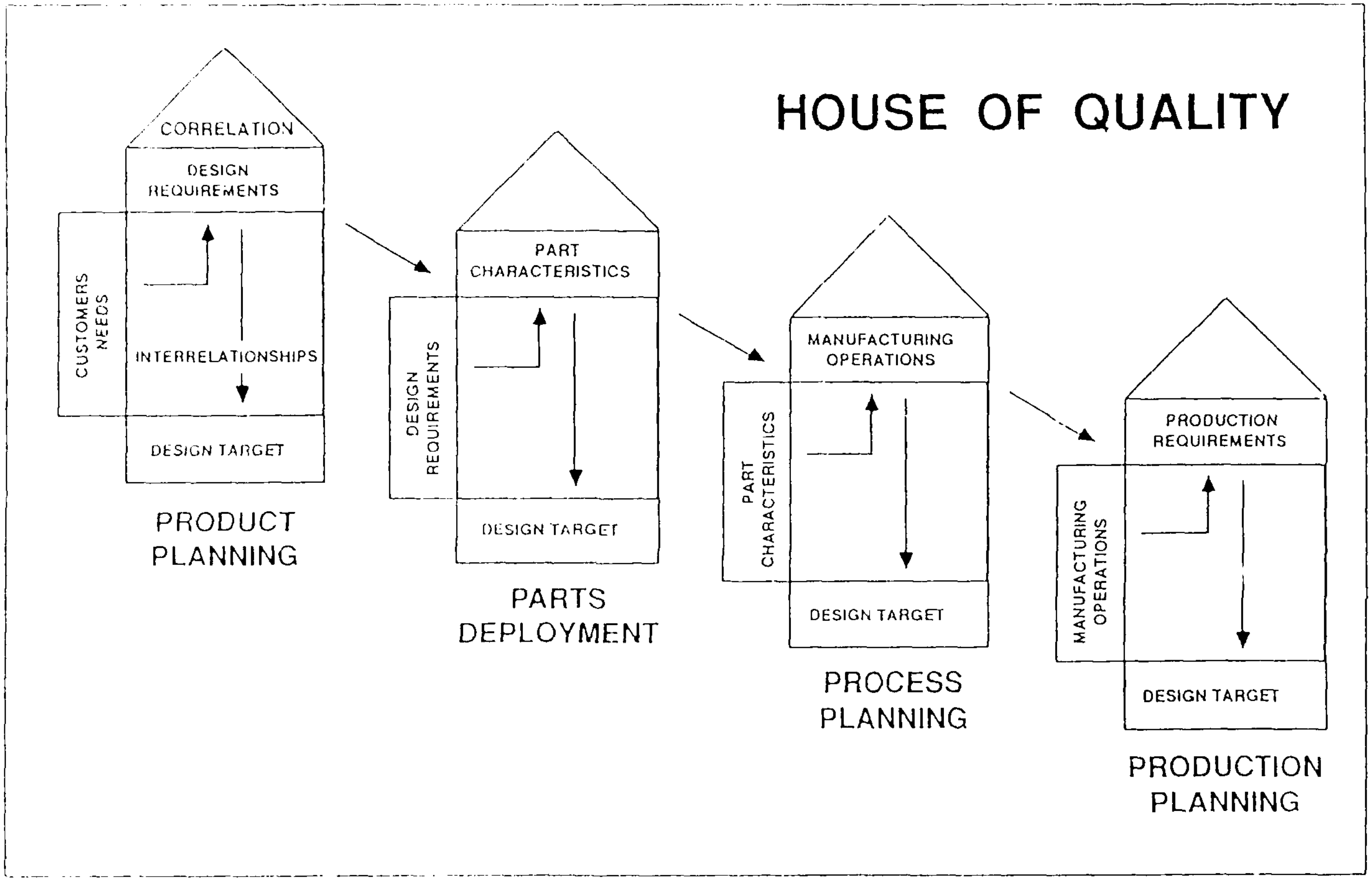


Figure 9

Quality Function Deployment (Source: ASI, 1988)

Michael A. Schubert provides an operational definition for QFD as follows:

> Quality Function Deployment is a method of "mapping" the elements, events, and activities that are necessary throughout the development process to achieve customer satisfaction. It is a technique oriented approach using surveys, reviews, analyses, relationship matrices, and robust designs all centered on the theme of translating the "Voice of the Customer" into items that are measurable, actionable, and potentially capable of improvement. (Schubert, 1988:132)

QFD is a means of transforming the "Voice of the Customer" into design parameters that can be deployed horizontally through product planning, engineering, manufacturing, assembly, and service. Therefore, QFD is a process used to identify conflicting design requirements that must be optimized while recognizing critical quality characteristics that must be controlled. The overall objective of QFD is to reduce the product development cycle while improving quality and decreasing cost. Thus, the effectiveness of QFD can be measured by the number of engineering changes made during product development, time cycle to the field, cost, and quality. Japanese companies, such as Toyota, have realized significant benefits in each of these areas. Using QFD, Toyota suppliers have reduced product development cycle time by thirty-three to fifty percent while improving quality and reducing costs by similar percentages (Sullivan, 1987b:1-4).

Statistical Process Control. Statistical Process Control (SPC) is an on-line method for reducing variability

in the manufacturing and assembling phases of production. SPC is the application of accepted statistical methods used to determine if a given process is within operating control limits. SPC determines if a process is statistically in control to produce a uniform defect-free product (McKee, 1985:Q6).

Quality assurance during production is primarily a function of statistical process control (Sullivan, 1986a:79). The control chart is the fundamental statistical tool for improving quality. A control chart is a graphic comparison of process performance data to computed control limits (Juran, 1980:288). The process performance data consist of chronological groups of data measurements obtained sequentially during production. The process performance data are then plotted on the control chart for the purpose of detecting assignable causes of variation. Assignable variation differs from random variation in that random variation is uncontrollable--induced purely by chance. However, assignable variation caused by specific "findable" causes can often be controlled. Ideally, a process should only be subject to random variation because random variation represents the smallest amount of variation possible in an established process. A process that is operating without assignable causes of variation is in a state of "statistical process control" (Juran, 1980:289).

In the Shewhart sense, the primary advantage of the control chart is to identify the causes of variability and to differentiate common (or random) variation from special (or assignable) variation so that laborers, engineers, and management can alter the process to reduce variability. Any process can be shown to appear in statistical control by changing the sampling method but this is not the premise behind the concept. It is desirable to have some measurements outside the control limits because these points represent causes of variability. Assignable causes of variability are potential sources of process improvement. If no measurements are outside the control limits, no refinement to improve the process can be accomplished and opportunity for improvement is lost. The Shewhart rule specifies a process is in control when two-thirds of the measurements fall within one-third of the limits with some measurements falling outside the limits. The next step is to change the process bringing all measurements inside the limits. Once the measurements are brought inside the limits, the limits should be redefined so that the process is always moving closer toward the target value. This continuously reduces variability by successive process improvements resulting from the narrowing of control limits (Sullivan, 1986a:80). It is important to note that control limits differ from specification limits as illustrated in Figure 10.

Design and manufacture as close to target values as possible,
not just within the specification limits.

```
UPPER PROCESS LIMIT      ------------------------------- 3/3
                         :
                         :------------------------------ 2/3
                         :       x         x
                         :-----------------------x------ 1/3
                         :   x         x               x
TARGET VALUE             :-x-------x-----x-----x--------
                         :         x               x
                         :------------------------------ 1/3
                         :     x             x
                         :------------------------------ 2/3
                         :                       x
LOWER PROCESS LIMIT      ------.-----.-----.-----.-----. 3/3

          SAMPLE NUMBER        3     6     9     12    15
```

Figure 10

SPC Control Chart

Walter Shewhart developed the control chart in the early 1920s as an aid for identifying potential problems in production before producing a defective product. The control chart allowed the worker to differentiate between random variation and assignable variation of a process. In the industrial environment, the worker is best situated to monitor the production process and discover assignable causes. However, management support is necessary to correct

these causes (Reid, 1985:Q3). In this case, a feeling of Participative Decision Making must exist for SPC to effectively reduce assignable variation.

Participative Decision Making. Participative Decision Making (PDM) is a concept which specifically refers to participation in the process of making a decision. PDM refers to operations where decisions about activities are made by the very persons who are to execute them and, as such, reflects a style of participative management (Lowin:1968).

Participative Decision Making may be considered a subsystem of Statistical Process Control. Guzzi (1987) defines PDM as "the mental and emotional involvement of a person in a group situation which encourages the person to contribute to group goals and share responsibility in them." PDM motivates the team member to use creativity, experience, and knowledge in contributing to the team's objectives versus simply issuing his or her consent to the objectives. This participation influences the individual to accept responsibility within the group for work outcomes (Guzzi, 1987:318). Within Statistical Process Control, Participative Decision Making plays a key role in that who better knows how to control variability on the production and assembly lines than the workers performing the actual work? Lawrence and Smith found "participative decision making has long been valued as a means not only of increasing organizational

efficiency and effectiveness but also of increasing employee involvement" (Lawrence and Smith, 1955:334-337). Mohr and Mohr determined that when employees were provided the chance to participate in the decision making process, their ingenuity and creativity often led to improved quality and production (Mohr and Mohr, 1983).

Troubleshooting Techniques for a Process. A process is the transformation of inputs into outputs while adding or creating value in either time, place, or form. Time value occurs when something is available **when** it is needed. Place value occurs when something is available **where** it is needed. And form value occurs when something is available **how** (in the form in which) it is needed. The basic process is illustrated in Figure 11.

A problem must first be identified before it can be corrected. Analytical studies are a prelude to corrective action on a process. However, prior to analytical study, the process must first be documented and defined. The three techniques most often used to understand, analyze, and prioritize problems within the process are the Process Flowchart, the Cause and Effect (Ishikawa/Fishbone) Diagram, and Pareto Analysis.

INPUTS		PROCESS		OUTPUTS
Manpower/Services		Transformation of inputs,		Manpower/Services
Equipment		value (time, place, form)		Equipment
Materials/Goods	--->	is added or created	--->	Materials/Goods
Methods				Methods
Environment				Environment

Figure 11

The Basic Process (Source: Gitlow, 1989:39)

The Process Flowchart. A process flowchart is a pictorial summary documenting the flow of the various operations of a process by depicting sequential steps involved in the process and showing the interrelationships between the steps (Gitlow, 1989:43).

Flowchart Symbols. To document a process, the American National Standards Institute, Inc. (ANSI) has approved a standard set of flowchart symbols as illustrated in Figure 12. Symbol shape and the information written within the symbol are useful in providing insight into a particular step of the process. Flowcharts are effective tools and simple to use when constructed properly. The following guidelines are recommended by Fitzgerald and Fitzgerald in constructing a flowchart (Fitzgerald and Fitzgerald, 1973:227-284).

1. Draw the flow chart from the top of the page to the bottom and from left to right.

2. Carefully define and clarify the activity being flowcharted.

3. Determine where the activity starts and ends.

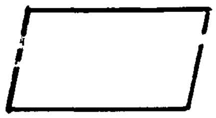
4. Describe each step of the activity using single-verb descriptions (i.e. design prototype)

5. Keep each step of the activity in its proper sequence.

6. Carefully observe the scope or range of the activity being flowcharted.

7. Use the standard (ANSI) flowcharting symbols. (Fitzgerald and Fitzgerald, 1973:227-284)

Basic Input/Output Symbol

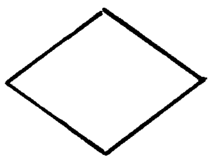


The general form that represents input or output media, operations, or processes is a parallelogram.

Basic Processing Symbol

The general symbol used to depict a processing operation is a rectangle.

Decision Symbol

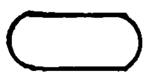


A diamond is the symbol that denotes a decision point in the process. This includes attribute type decisions such as pass-fail, yes-no. It also includes variable type decisions such as which of several categories a process measurement falls into.

Flowline Symbol

A line with an arrowhead is the symbol that shows the direction of the stages in a process. The flowline connects the elements of the system.

Start/Stop Symbol



The general symbol used to indicate the beginning and the end of a process is an oval.

Figure 12

Flowchart Symbols (Source: Silver and Silver, 1986:142-147)

Cause and Effect Diagrams. Cause and Effect Diagrams are useful when applied under conditions of collective efforts. Cause and Effect analysis is used after brainstorming to organize the information produced in the brainstorming session. Analysis includes gathering and organizing possible reasons or causes of the problem, selecting the most probable cause, and verifying the possible causes until a valid cause and effect relationship is established. Also known as a Fishbone or Ishikawa Diagram, the Cause and Effect Diagram depicts the linkage between the causal factors and the problem (Gitlow, 1989:382-387).

An illustration of a generic Cause and Effect Diagram is shown in Figure 13.

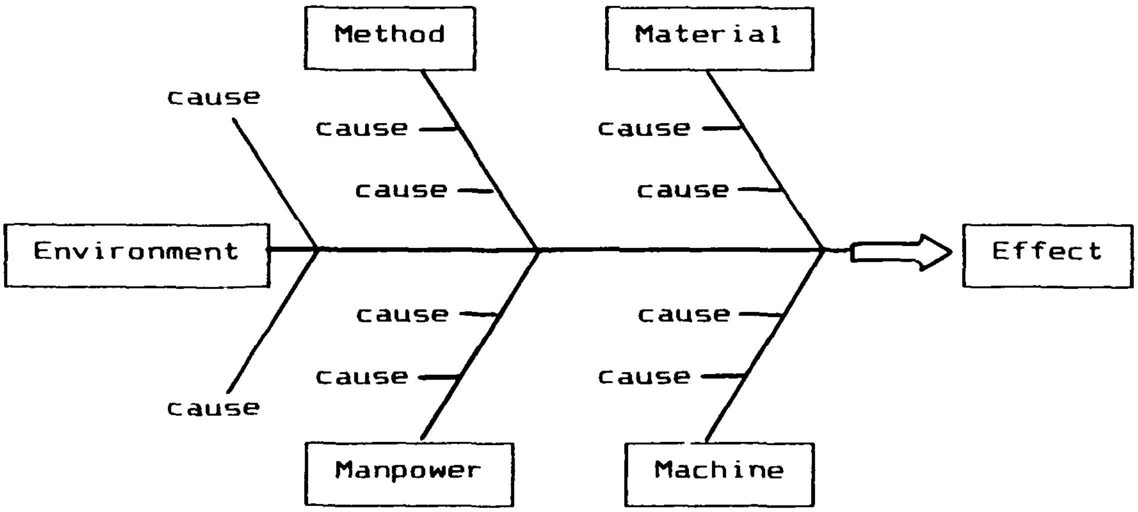


Figure 13

Generic Cause and Effect Diagram (Source: Gitlow, 1989:383)

Cause and Effect Diagrams are helpful in organizing efforts to improve the process when a process is stable. If a process is chaotic, the Cause and Effect Diagram can identify areas where attention can be focused to stabilize the process (Gitlow, 1989:382-387).

The purpose of using a cause and effect diagram is to understand the factors affecting a process. Gitlow suggests the following steps for creating a Cause and Effect Diagram.

1. Clearly define and state the problem. After the problem has been clearly defined, write it on the right side of a flip chart and draw an arrow to it.

   -----------------------> Problem

2. Identify major causes. A common method of determining the major causes is to consider the impact of machines, methods, material, manpower, and the environment on the problem.

3. Brainstorm sub-causes to uncover all of the possible sub-causes that contribute to the problem being studied and record the sub-causes on the diagram. It is important to note that only causes of the problem should be discussed at this point--not solutions.

4. Allow time to ponder the causes before evaluating them. Also consider interactions among the causes.

5. On the Cause and Effect Diagram, circle the likely causes of the problem under study.

6. Verify the most likely cause of the problem under study by collecting and analyzing data to ascertain if it has a significant impact on the problem. If the most likely cause does not have a significant impact on the problem, the group should then verify the next most likely choice to determine its impact on the problem, and so on until a viable solution to the problem is discovered. (Gitlow, 1989:382-385)

Pareto Analysis. Pareto Analysis is a tool used to identify and prioritize problems. Vilfredo Pareto, an Italian economist, originated the concept of "the vital few versus the trivial many." The vital few are the few factors that account for the largest part (percentage) of the total. The trivial many account for the rest. From the Pareto concept, Lakelin formulated the 80-20 rule which states that approximately 80 percent of the value, costs, or problems come from 20 percent of the elements (Gitlow, 1988:389-390).

As depicted in Figure 14, the Pareto diagram is a simple bar chart with the bars representing the frequency of each problem arranged in descending order so that the tallest bars are on the left side of the chart and descend to the right.

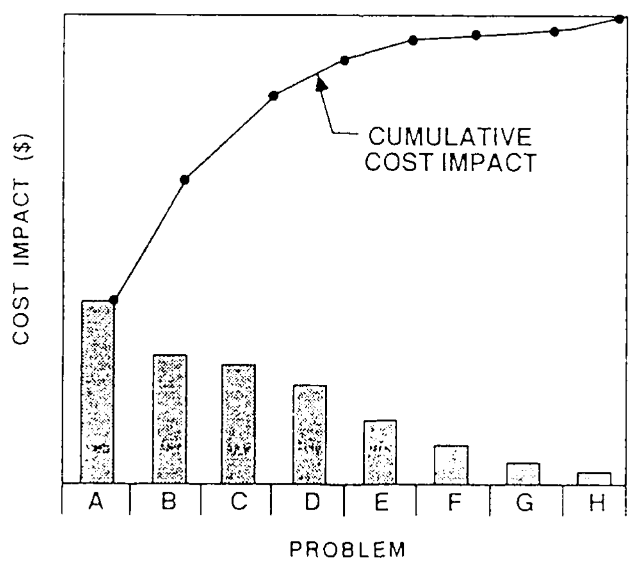


Figure 14

Pareto Diagram (Source: VRP, 1989:B17-b)

While Pareto analysis is commonly viewed as a problem solving tool, its primary use is in determining what problems to solve rather than how to solve them (Ishikawa, 1976:43).

Ishikawa recommends the following steps in constructing a Pareto diagram.

1. Establish categories for the data being analyzed--classifying data according to defects, products, work groups, size, and other appropriate categories.

2. Specify the time period during which data will be collected. Three important considerations in establishing a time period to study are:

   a. the selection of a convenient time (i.e. one hour, one day, one week, one month, etc.).

   b. the selection of a time period should be constant for all related diagrams for purposes of comparison.

   c. the selection of the time period should be relevant to the analysis.

3. Construct a frequency table arranging the categories from the one with the largest number of observations to the one with smallest number of observations. The frequency table should include a

   a. category column;

   b. frequency column (indicates the number of observations per category with a total at the bottom of the column);

   c. cumulative frequency column (indicates the number of observations in a particular category including all frequencies in categories above it);

   d. relative frequency column (indicates the percentage of observations within each category with a total at the bottom of the column;

   e. relative cumulative frequency column (indicates the cumulative percentage of observations in a particular category plus all categories above it in the frequency table).

4. Construct the Pareto Diagram.

   a. Draw horizontal and vertical axes on graph paper.

   b. Mark vertical axis with the appropriate units starting at zero continuing up through the total number of observations in the frequency table.

   c. Under the horizontal axis, write the most frequently occurring category on the far left hand side with the next most frequently occurring category immediately to its right, and so on continuing in decreasing order.

   d. Draw in bars for each category.

   e. Plot a cumulative line indicating a cumulative percent scale on the right side of the chart. This is done by starting in the lower left hand corner and progressing diagonally to the top right corner of the first column.

   f. Title the diagram and briefly describe its data sources. (Ishikawa, 1983:43-44)

<u>Taguchi Methods</u>. Genichi Taguchi is a Japanese statistician and engineer whose views on industrial productivity and quality have significantly influenced both the Japanese and American quality arenas. Many Japanese firms have achieved great success through the application of Taguchi Methods. Thousands of engineers have reportedly conducted tens of thousands of experiments based on his teachings (Wu, 1982). For his contributions to quality, Taguchi has been awarded some of Japan's most prestigious management awards--including the Deming Prize. Taguchi's quality techniques, methodologies, and philosophies have had a major impact on America's quality perspective.

<u>Quality</u>. Taguchi views quality in terms of "loss to society." Taguchi looks at quality not in terms of value added but in terms of "the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions" (Taguchi, 1985:7). Within this context of quality, Taguchi restricts loss to two categories:

1. Loss caused by variability of function
2. Loss caused by harmful side effects (Taguchi, 1985:7).

An example of harmful side effects can be illustrated by the medicine thalidomide. In the early 1960's, thalidomide was used extensively as a sedative and sleeping pill. Whereas thalidomide's functional performance as a sedative was superb, its use was discontinued when it was discovered to cause severe malformation in limbs of developing fetuses very early during intrauterine life (Thomas, 1975:T-24). Therefore, a product with good quality should perform its intended functions without variability and without loss through harmful side effects.

Whereas much emphasis has been placed on Taguchi's statistical techniques, the locus of his message centers on the conceptual framework of the quality improvement process. When approached from this perspective--according to Gunter, two fundamental concepts set the basis for Taguchi's principles.

1. Quality losses must be defined as deviation from target, not conformance to arbitrary specifications; quality losses must be measured by systems wide costs in terms of "loss to society" and not local costs at points of defect detection.

2. Achieving high system quality levels economically requires quality to be designed in. Quality cannot be achieved economically through inspection and product screening; the three stages of quality by design are: (1) systems (functional) design; (2) parameter (targeting) design; and (3) allowance (tolerance) design. Systems and parameter design provide the greatest opportunity for quality cost reduction; allowance design often entails increased costs to achieve higher quality. (Gunter, 1987:44)

As a product deviates from its design target, quality deteriorates and the costs of rework and scrap encountered in the "hidden factory" rapidly accumulate, continuously increasing as the product progresses through each phase of the manufacturing cycle. Therefore, it is more efficient to design in quality than to try to inspect in quality. It is extremely costly to re-engineer a poor design after production has started or even worse, after the product reaches the customer.

<u>The Taguchi Loss Function</u>. The essence of Taguchi Methods involves a concept called the quality loss function--a method of quantifying product and process quality (in terms of dollars). Understanding the quality loss function is vital to understanding Taguchi Methods. The concept is predicated on 200-year-old mathematical foundations of statistics established by Gauss and has been a focal point for statistical decision theory over the last 40 years.

The way the loss function is established is determined by the type of quality characteristic. A quality characteristic is how performance (quality) is measured. According to the American Supplier Institute, there are five types of quality characteristics:

1. Nominal the Best (achieving a desired target value with minimal variation). For example, dimension and output voltage.

2. Smaller the Better (minimizing a response). For example, friction, shrinkage, and wear.

3. Larger the Better (maximizing a response). For example, pull-off force and tensile strength.

4. Attribute (classifying and/or counting data). For example, appearance.

5. Dynamic (response varies depending on input). For example, the fan drive speed should vary depending on the temperature of the automotive engine. (ASI, 1988:I-20)

A "Nominal Value is Best" characteristic will be examined to illustrate the loss function. Simplistically, the concept can best be illustrated by points along a quadratic curve. As these points deviate farther away from the target value on the curve, an associated loss of quality accompanies this deviation. **A key concept of Taguchi's Loss Function is that a product does <u>not</u> start causing losses <u>only</u> when it is out of specification, but causes a loss whenever there is any deviation from the target value.**

As depicted in Figure 15, a central target (T) represents the ideal state of the design parameter (or ideal target value). Specification limits (S), denoted by T + S

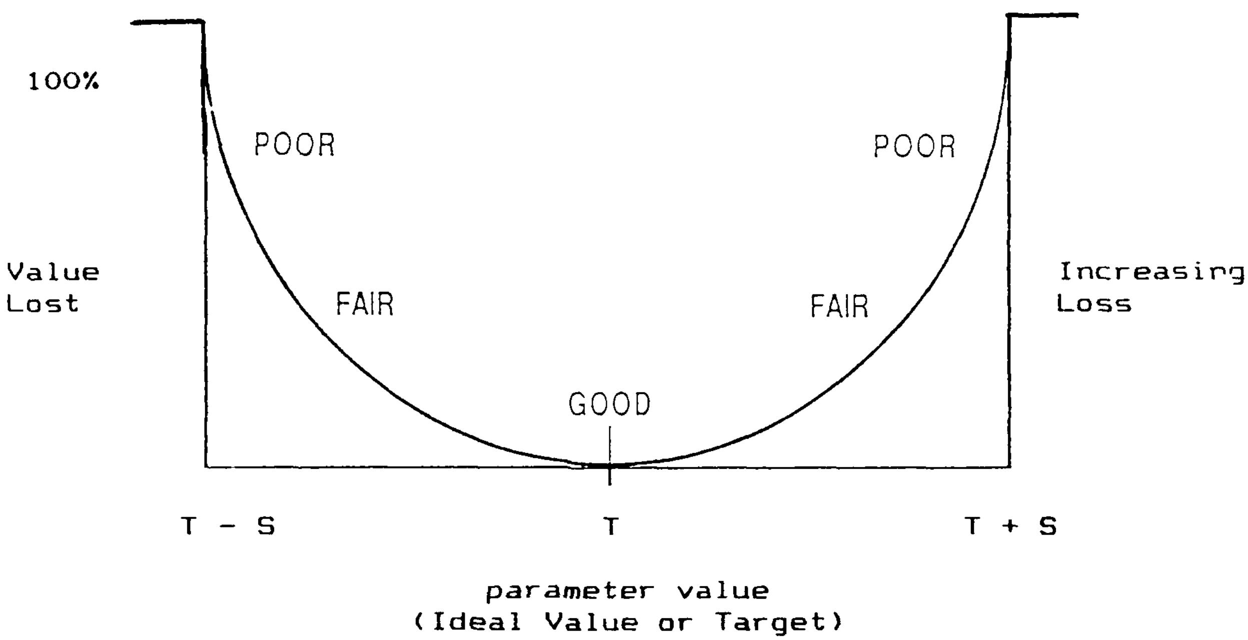


Figure 15

The Loss Function

and T - S represent standard symmetric upper and lower specification limits. The vertical axis measures value lost due to deviation away from the ideal target value.

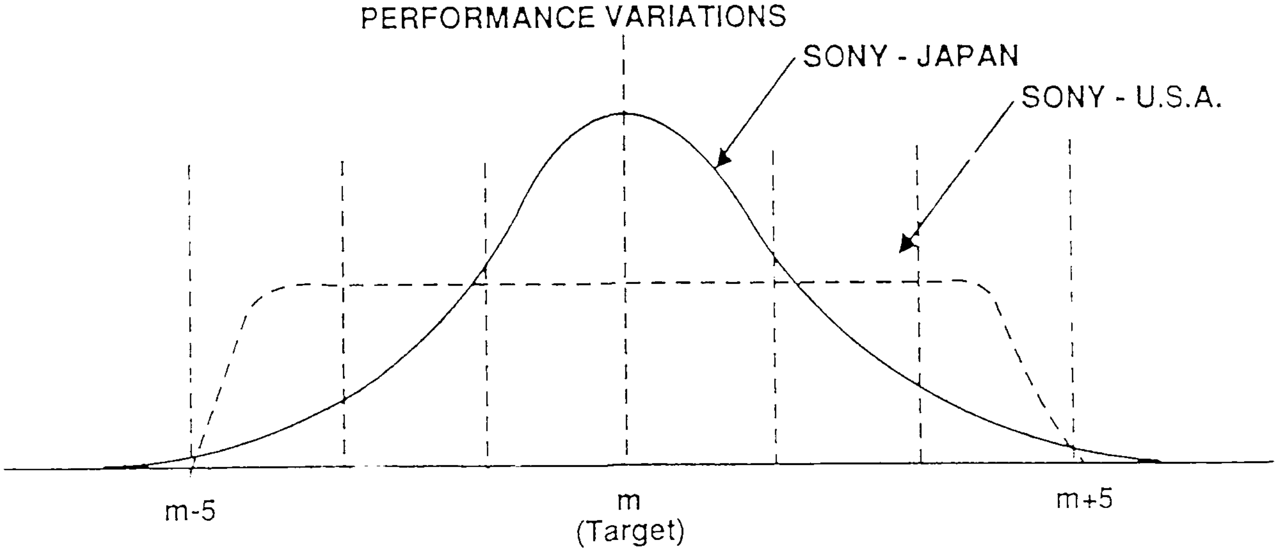
This basic explanation of Taguchi's loss function is indeed an oversimplification. Ideal target values and specification limits are necessary entities of the concept and setting the values associated with these entities are as important as the concept itself. Moreover, as the measure of quality deviates from its ideal target value, there is no instantaneous change from perfect to useless at some arbitrary point. Instead, there exists a gradual deterioration of performance as the quality measure shifts away from the target value. In fact, deterioration can continue even beyond the specification limits. Greater than 100 per cent losses beyond the totality of individual value can occur when poor performance of a single component within an assembly results in the destruction of the entire assembly. In reality, the precise shape of the loss function curve illustrated in Figure 15 is extremely difficult if not impossible to calculate. However, good approximations of the curve can prove to be very useful (Gunter, 1987:45).

Within the context of Taguchi's Loss Function, it is important to comprehend how value is defined. Value is not merely measured on a scale of 0 per cent (no value lost) to 100 per cent (all value lost). Taguchi defines value lost in terms of "the losses a product imparts to the society from the time a product is shipped" (Taguchi and Wu, 1980). From this definition, the customer oriented emphasis that Taguchi places on quality can clearly be seen (Gunter, 1985:45).

Taguchi's approach to quality emphasizes that quality losses begin whenever there is any deviation from the target value. Therefore, quality is best achieved by minimizing variance rather than by strict conformance to specification.

A classic example supporting the relationship between reducing variation and increasing quality is depicted in Figure 16. In 1979, an article appeared in the Asahi, a Japanese newspaper, addressing American consumer preference for Sony televisions built in Japan over Sony televisions built in the United States. The Sony televisions had been manufactured in two plants using identical designs and tolerances. One plant was located in Tokyo, Japan, and an identical subsidiary plant had been built by Sony in San Diego, California. Even though the U.S. plant produced sets that were defect free (i.e. no sets were produced with out-of-tolerance color density) and the Japanese plant produced televisions with a defect rate of 3 per 1,000 units (color density out-of-tolerance in 3 out of 1,000 sets), the American consumer preferred the Sony televisions built in Japan. Japanese built Sonys were perceived as having better quality than the sets built in the United States because the color density of the Japanese sets was manufactured closer to the target value (despite having 3 defects per 1,000). Although Japanese and American made televisions were manufactured to identical tolerances, customers were clearly able to see the difference produced by Variability Reduction.

DIFFERENCE IN PRODUCTION QUALITY BETWEEN JAPAN AND USA



DISTRIBUTION OF COLOR DENSITY IN TV SETS

SPECIFICATION: m $\pm$ 5

TYPES OF DISTRIBUTION

SONY CASE CITED FROM THE ASAHI, APRIL 17, 1979

FACTORY LOCATION	APPROX. TYPE OF DISTRIBUTION	PERCENT DEFECTIVE
SAN DIEGO	UNIFORM	ALMOST ZERO
JAPAN	NORMAL	0.3%

Figure 16

Difference in Sony Production Quality
Between Japan and USA (Source: ASI, 1988:II-5)

Thus, tolerances alone do not ensure quality. They merely dictate the limits of product functionality. As illustrated in Figure 16 by the Sony television example, two products can both function within identical specifications but one can still be superior relative to the other. Manufacturing every product exactly to desired nominals is essential in ensuring quality. This is an important aspect of Variability Reduction.

As depicted in Figure 17, the loss function can be represented by an equation that includes a cost constant which is based on costs and specification limits, the variance which measures the variability or spread of a distribution, and the desired target. Losses for a given cost constant can be decreased by reducing the variance and staying close to the target value.

The Loss Function

$$\text{Loss} = C(S^2 + (\bar{x} - T)^2)$$

where:

C = Cost Constant

S^2 = Variance

$\bar{x}$ = Average

T = Target

Figure 17

The Mathematical Loss Function (Source: Ross, 1988:42)

Prior to production, off-line quality engineering should reduce variance through design and establish the design target for the lowest loss (Ross, 1988:41-43).

Functional Performance. Taguchi's second fundamental concept addresses the importance of economically achieving high quality in terms of consistency of functional performance. To achieve this, the design must be robust to variation caused by materials, manufacturing, and use. Taguchi segregates the design cycle into three phases as shown in Figure 18. The first phase is systems design, in which the fundamental design and engineering concept is established. The second phase is parameter design, which establishes design nominals such as target dimensions, material composition, temperatures, voltages, etc. The third phase is allowance design, which specifies the tolerances (Gunter, 1987:47).

	SYSTEM	PARAMETER	ALLOWANCE
	Set Concept	Set Target	Set Tolerance
through:	-engineering	-engineering -statistical design -sensitivity analysis	-engineering -statistical tolerancing -experimental design

Figure 18

Three Phases of the Design Cycle (Source: Kackar, 1987:22)

System Design. The initial engineering effort encompasses system design. Application of scientific and engineering knowledge produces a basic functional prototype design. In conjunction with appropriate technologies using engineering modeling and judgment, this design delineates the initial settings of product or process parameters. Understanding the customer's needs and the manufacturing environment are essential to a successful system design phase (Kacker, 1987:68).

System Design is a concept-oriented activity involving little or no need for statistical methods. Nevertheless, it is an important stage. It is the stage in which the initial engineering effort attempts to find a good system to perform the function expected from the product. Using an FB-111 as the design prototype to fly a 20-hour bombing mission would be a functional but non-optimum system for the 20-hour mission because of the FB-111's limited range and refueling requirements. In this case, a B-52 with its longer range would be a more appropriate system--less sensitive to functional variations inherent through the dependency of multiple aerial refuelings. Therefore, knowing the function of the system, the operating environment, and the dependent variables affecting the system are critical facets of efficient system design.

Parameter Design. Parameter Design is the second phase of Taguchi's Design Cycle. Parameter Design is

the process of selecting the settings of product or process parameters which decrease the sensitivity of engineering designs to sources of variation (Kackar, 1987:68). The goal of Parameter Design is to set product or process parameter values to develop a high performance product which has minimum sensitivity to noise. The purpose of this phase is to yield a robust product or process. Robustness renders a product or process insensitive to the effects of variability or "noises" from the environment, manufacturing processes, and deterioration in use (Hull, 1988:5).

A Parameter Design experiment typically considers two types of factors--Control Factors and Noise Factors. A Control Factor is a factor whose values can be selected and maintained by the experimenter. A Noise Factor is a factor whose values cannot or will not be selected or maintained but can affect the performance of the functional characteristic. Parameter Design examines the interactions between Control Factors and Noise Factors seeking parameter levels where a characteristic is stable and robust (insensitive to noise).

The purpose of parameter design is to identify product design characteristics that render product performance less sensitive to the effects of environmental factors, product deterioration, and manufacturing variations. Environmental factors are conditions that exist in the environment in which the product will be used and include human variations in operating the product. Product deterioration consists of the

changes in product parameters over time from wear and tear on the product during its life cycle. Manufacturing variations are the manufacturing conditions that cause product production to deviate from its nominal values (Gitlow, 1989:501).

Environmental factors, product deterioration, and manufacturing variations are three common sources of product variation. They are classified as common sources of variation because they are chronically present and affect product performance. Decreasing the sensitivity of engineering designs to these sources of variation ultimately provides a robustness in product design--creating a robust product (a product insensitive to variation) with improved field performance.

Parameter design is an essential step in achieving robustness and high quality products without increasing cost. The main objective of parameter design is to determine the nominal values for the control factors maximizing product performance with the least sensitivity to noise and to do this at the least cost. In Japan, forty percent of the engineering time is spent on parameter design compared to only 2 percent in the United States (VRP Guidebook, 1989:15).

Design of Experiments. Design of Experiments (DOE) is a technique valuable in resolving complex problems--improving both product designs and manufacturing processes. DOE's objectives are to identify critical parameters, isolate

the causes of variation, and improve technical or operational characteristics enhancing quality. The experimental results provide a better understanding of the process and can be used to conduct parameter design. Parameter design, a logical continuation of DOE as shown in Figure 19, is a technique used to analyze the experimental data ultimately yielding robust designs by selecting the optimum product and process parameters that minimize variability and provide better performance over a wider range of operating conditions and environments (VRP Guidebook, 1989:14).

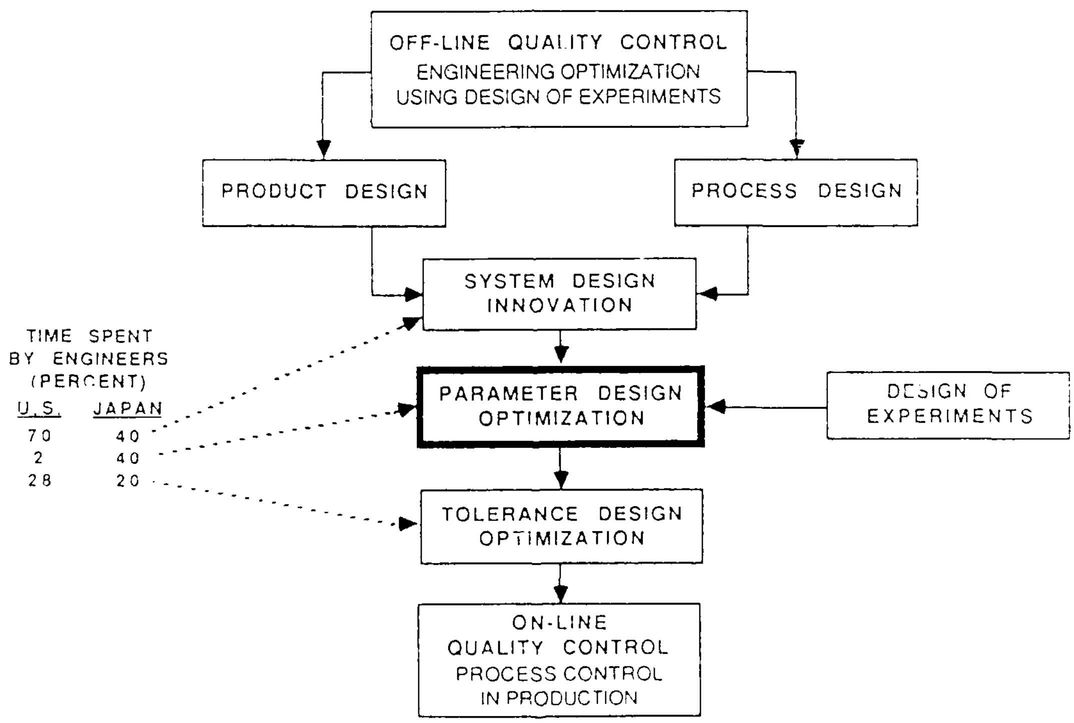


Figure 19

Quality Control Steps (Source: VRP Draft, 1989:B-15a)

The use of Variability Reduction techniques such as Design of Experiment and Parameter Design is growing in the United States. Government contractors are already experiencing substantial increases in quality through the use of these tools. Recently, Aerojet Ordnance, a government owned munitions plant, was experiencing a serious problem in producing the ADAM mine. Although SPC was in use and twelve of thirteen processes were within their tolerances, nineteen out of twenty-five lots were rejected. Aerojet Ordnance used a Taguchi experiment to identify the critical parameters. Selecting the thirteen parameters used in the SPC program, Aerojet Ordnance tested the parameters at three different levels. Conducting only twenty-seven experiments firing six rounds each, four parameters were determined to be critical. With these parameters set at their best levels, the process yielded good lots without any rejects. The other nine parameters were deemed less important and their tolerances could be relaxed. The results of the experiment were impressive--production schedule met while achieving significant cost savings (VRP Guidebook, 1989:B-16).

The ultimate purpose of parameter design is to produce a robust product or process. Robustness renders a product or process insensitive to the effects of variability or "noises" from the environment, manufacturing processes, and deterioration in use. To minimize loss, a product must be produced at optimal levels with minimum variation in its

functional characteristics. Factors affecting a product's functional characteristics are control factors and noise factors. Control factors are factors that are controlled relatively easily, such as materials and processing. Noise factors are nuisance variables that are difficult, costly, or impossible to control, such as ambient temperature, humidity, and customer use.

Noise. Noise variables consist of all the factors causing product performance characteristics to deviate from their nominal value or cause a deterioration in actual performance when compared to desired performance. There are three categories classifying sources of noise--outer noise, inner noise, and between product noise. Outer noise (or external sources of noise) are variables external to the product that can affect product performance. Variations in environmental variables such as temperature, humidity, and dust as well as variations in product operation induced by human inputs are examples of outer noise. Inner noise (or internal sources of noise) are deviations of actual characteristics of the manufactured product away from its nominal settings. Inner noise may be caused by product deterioration or by imperfections caused by the aging of machinery or tolerances used during processing (Kackar, 1985:180). Between product noise results from piece to piece variation caused by manufacturing imperfections. Noise factors are generally responsible for causing a product's

functional characteristics to deviate from its target value. Selecting values for control factors that make a product or process insensitive to changes from noise factors makes a product robust. Instead of finding and eliminating the causes of noise factors, the intent is to remove or reduce the impact of the causes. This yields a robust product--a product robust against noise (ASI, 1988:I-32).

The purpose of a parameter design experiment is to determine the nominal values for design parameter variables that will produce the lowest impact on product performance characteristics by noise variables. These nominal values are established by systematically varying their settings in conjunction with a selected combination of noise variable settings, and then comparing the resultant performance characteristics.

For example, the performance characteristic of interest when considering an electrical circuit design is the output voltage of the electric circuit, y, and its target value, y_0. Assuming the output voltage of the circuit is determined by the gain of transistor X in the circuit, the circuit designer is free to choose the nominal value of this gain. Since the effect of the transistor gain on the output voltage is nonlinear and the circuit designer selects a nominal value of transistor gain to be x_0, an output voltage of y_0 is obtained. If the actual transistor gain deviates from the nominal value of x_0, the output voltage will deviate from y_0

as shown in Figure 20 resulting in a large variation in output voltage. One way of reducing the output variation is to use an expensive transistor whose gain has a very narrow distribution around x_0. However, this is not cost effective. Another way to reduce output variation is selecting a different value of transistor gain. In this case, if the nominal transistor gain is x_1, the output voltage will have a much smaller variance about y_1. However, the mean value y_1 is far from the target value y_0. Now suppose another component in the circuit, such as a resistor, has a linear effect on the output voltage and the circuit designer is free to choose the nominal value of this component. The circuit designer can then adjust this component to move the mean value of voltage from y_1 to y_0. Adjustment of the mean value of a performance characteristic to its target value is usually a much easier engineering problem than the reduction of performance variation (Kackar, 1986:26).

When the circuit is designed so that the nominal gain of transistor X is x_1, an inexpensive transistor can be used because having a wide distribution around x_1 results in reduced variability about y_1. Figure 20 illustrates the concept of exploiting the nonlinear effects of product or process parameters on product performance characteristics. This can be an effective means for reducing the sensitivity of product performance to environmental factors, product deterioration, and manufacturing variations while

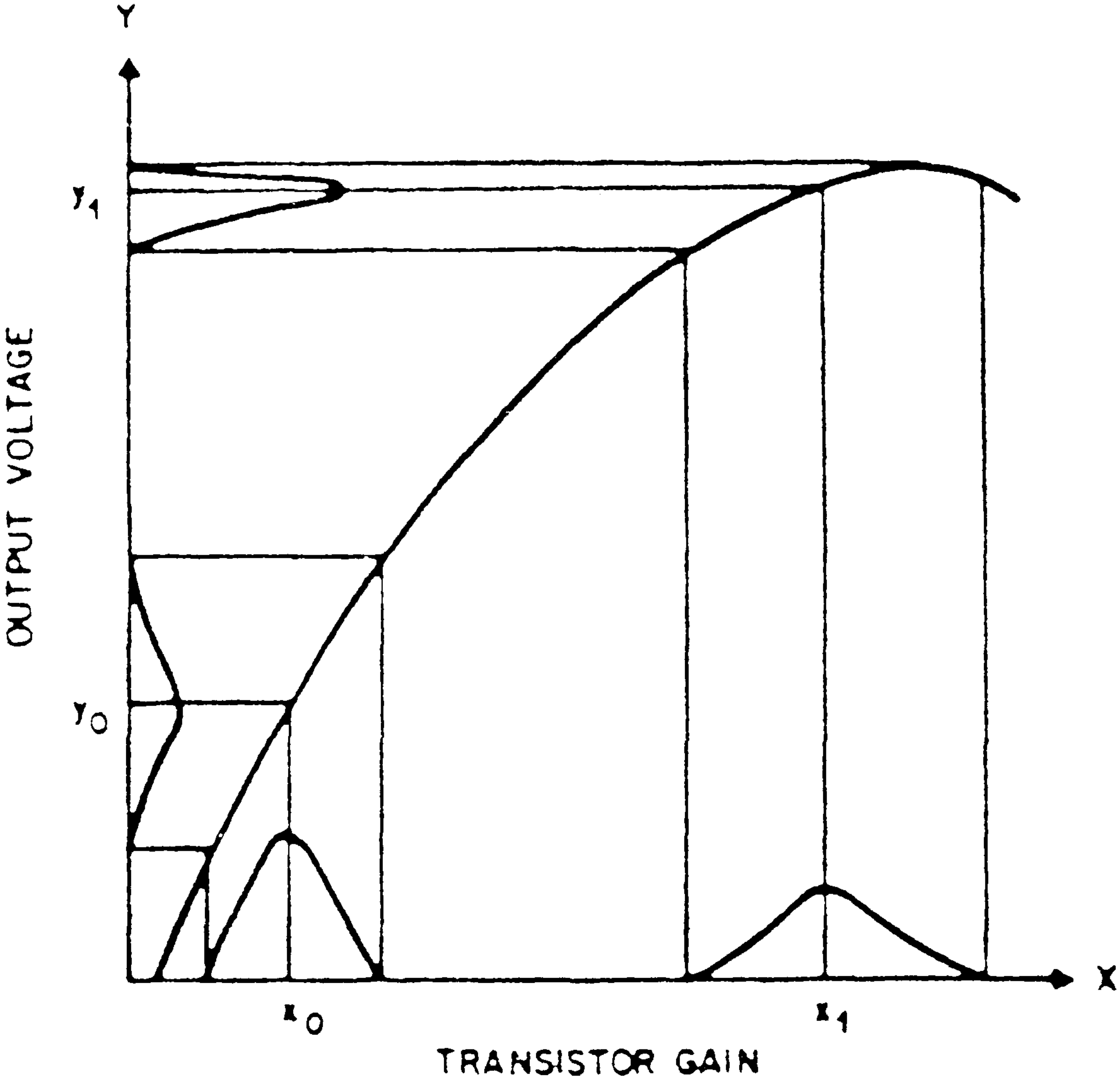


Figure 20

Exploiting Nonlinear Effects of Process or Product Parameters on Product Performance (Source: Kackar, 1986:26)

simultaneously reducing costs (Kackar, 1986:26).

In reality, it may be impossible to consider every potential noise variable in the parameter design experiment due to the large data requirements. However, the design engineers conducting the parameter design experiment should understand the importance of all applicable noise variables and constantly be wary of potential problems from unknown sources of noise variables (Gitlow, 1989:504).

In conducting the parameter design experiment, the experimenter systematically varies the levels of the most significant noise variables to determine their effects upon the product's performance characteristics. Selecting parameter design variable settings and noise variable settings for a parameter design experiment can become complex. Taguchi devised a procedure for performing the parameter design experiment using a design parameter variable matrix and a noise variable matrix. The design variable matrix lists the design variables in its columns and the appropriate combinations of parameter design variable settings in its rows. Similarly, the noise variable matrix lists the noise variables in its columns and the appropriate combinations of noise variable settings in its rows. The experiment involves conducting tests for every row in the design parameter matrix under the conditions specified in every row of the noise variable matrix. The outcomes (or the resulting performance characteristics) are recorded for each

specified combination of design parameter variables and noise variables. Within each configuration of design parameter variables, all the test run settings of the noise variables shown in the noise variable matrix are used to compute a performance statistic. Performance statistics estimate the effects of the noise variables on the performance characteristics for a given design. The setting of the parameter design variables yielding the best performance statistic is selected as the best product design (Gitlow, 1989:505).

Taguchi advocates using a performance statistic designated as a signal-to-noise ratio. Three types of signal-to-noise ratios are:

1. The smaller the ratio the better the product design. For example, if friction is the performance characteristic under study, low friction is desirable.

2. The larger the ratio the better the product design. For example, if tensile strength is the performance characteristic under study, high tensile strength is desirable.

3. A nominal value is best. For example, if a gap size specification of 2.255 mm is the performance characteristic under study, a precise gap size of 2.255 mm is most desirable (ASI, 1988:I-40).

Statistically designed experiments using signal-to-noise ratios to evaluate process or product performance can be useful in reducing variation through the appropriate selection of parameter settings. Design parameters for robustness are identified using signal-to-noise ratios.

Tolerance Design. Tolerance Design is the process of specifying tolerances and the nominal settings defined during the parameter design phase. Historically, industry rarely assigns tolerances scientifically, routinely assigning tolerances by convention. Tolerances that are too narrow result in high manufacturing costs and tolerances that are too wide increase performance variation. Therefore, practical tolerance design necessitates a tradeoff between the customer's loss function and manufacturing costs (Kacker, 1987:69).

Design engineers are forced to use tolerance design when the influences of environmental factors and product deterioration cannot successfully be reduced through parameter design. Tolerance design should be performed after parameter design because it is less expensive to reduce performance variation through parameter design than it is to control performance variation through the establishment of tolerances. However, having to resort to tolerance design does not force an abandonment of "continuous improvement" as engineers will continuously attempt to produce a better design by establishing nominal values which reduce performance variation (Gitlow, 1989:503).

Data Organization

The first step in developing a Variability Reduction Process Handbook for Air Force managers was to examine Air Force policy concerning Variability Reduction. Policy Letter

#6 from General Hatch establishes VR policy directing acquisition commands to derive maximum benefit from the Variability Reduction Process by 1993. The policy letter also stipulates four specific objectives which provide a basis for developing the handbook.

Further research indicated that the Variability Reduction Process was a building block of the R&M 2000 Process, which is considered by many to be a subset of DoD's Total Quality Management initiative. The philosophies behind these initiatives coupled with General Hatch's policy letter provided clear guidance as to the direction a Variability Reduction Process Handbook should take.

Once the information pertaining to the Variability Reduction methodologies was collected and analyzed, the next step was to consolidate the information into a useful form.

Handbook Development

After collecting, organizing, and analyzing the data, the research process was complete. What was accomplished next involved producing the end product--a Variability Reduction Process Handbook that could assist Air Force personnel involved in Air Force acquisition. The format and content of the handbook is important as it is vital to present complex concepts as simply as possible. The handbook had to be understandable to be useful. Therefore, the format chosen consists of graphs, bullet statements, and pictorial descriptions displayed on the right or odd numbered pages,

accompanied with text explaining the graphs, bullets, and pictorials displayed on the left or even numbered pages.

First, the handbook explains how Variability Reduction fits into the TQM initiative and R&M 2000 Process. Then, QFD, SPC, Troubleshooting Techniques, and Taguchi Methods are defined and examined along with their various subsets. Next, a glossary of terms is included to provide quick reference to a consolidated listing of definitions associated with variability reduction. Lastly, a bibliography comprises the final section of the handbook providing sources for further reference into quality management techniques.

Handbook Validation

The Variability Reduction Process Handbook was evaluated and validated by Air Force sources. Among those taking place in the evaluation and validation process were AFIT/LSM and HQ USAF/LE-RD. Lastly, the handbook was submitted to HQ USAF/LE-RD for final approval.

III. Findings

Overview

This chapter presents the results of the research as the following investigative questions were answered.

1. What official guidelines and directives exist within the USAF pertaining to VRP?
2. What Variability Reduction methodologies should be covered in a Variability Reduction Process Handbook?
3. How can the effects of VRP be measured?

Existing Guidelines and Directives

The researcher found four official sources addressing Variability Reduction, of which two were still in draft form. Policy Letter #6: R&M 2000 Variability Reduction, dated 14 July 1988, and USAF R&M 2000 Process, dated July 1988, were the two officially published documents addressing Variability Reduction.

Policy Letter #6: R&M Variability Reduction is the governing Variability Reduction directive. Policy Letter #6 from General Monroe W. Hatch, Jr., Vice Chief of Staff, USAF, establishes Air Force policy regarding Variability Reduction to improve the quality, reliability, and maintainability of Air Force systems at reduced costs. This policy applies to acquisition and post-production support of all Air Force systems, subsystems, and equipment and directs acquisition

commands to derive maximum benefit from the Variability Reduction Process by achieving the following objectives by 1993:

a. Ensure validated user requirements are the basis for all actions.

b. Develop new systems or modifications/upgrades to existing systems simultaneously with their production processes. Ensure that the product and the process are as fully integrated as possible to meet user requirements at the lowest possible cost. Evaluate progress in this area during each design review.

c. Reduce performance variations in both the product and the manufacturing process until reaching the most cost-effective level. Assess cost effectiveness using the monetary loss function.

d. Conduct training in variability reduction concepts and techniques for personnel working in acquisition and repair activities. (General Hatch, 1988)

USAF R&M 2000 Process is a booklet describing how to increase combat capability while saving resources through good R&M management. The scope of the booklet applies to all Air Force mission areas, all programs, and all types of procurements. Variability Reduction is designated as a building block in USAF R&M 2000 Process. These building blocks are viewed as "preferred" practices for Air Force programs and should be tailored based on the type of program and the acquisition strategy (USAF R&M 2000 Process, 1988:ii).

In addition, there were two other sources, albeit in draft form, addressing Variability Reduction. The draft copy of DoD 5000.51-G, Total Quality Management, A Guide for

Implementation, provides a cursory view of the Loss Function, QFD, SPC, and R&M 2000 VRP with a single page account discussing the what, why, and how of each (DoD 5000.51-G, 1989:42,55,56,74). The final source consisted of a draft Variability Reduction Process Guidebook, being developed under contract by HQ USAF/LE-RD. The researcher obtained a rough draft of this guidebook and it is worthy to note that the issues covered in the contracted guidebook were similar to those included in the researcher's handbook.

VRP Methodologies Selected for the Handbook

The research focused primarily on four Variability Reduction methodologies for inclusion in the handbook. These methodologies were Quality Function Deployment, Statistical Process Control, Troubleshooting Techniques, and Taguchi Methods. The justification for these methods is as follows. QFD and SPC appeared to be the most widely accepted methods for Variability Reduction per telephone interviews with HQ USAF/LE-RD and several AFLC divisions and branches at Wright-Patterson AFB. Additionally, QFD and SPC were addressed both in the USAF R&M 2000 Process and the draft copy of DoD 5000.51-G. Taguchi Methods had strong support from many other sources as embodied in the literature review, especially in the areas of Taguchi's Loss Function, Parameter Design, and Design of Experiments. Although Taguchi did not invent Parameter Design, he was the first to successfully combine the concept with Design of Experiments. Also, the

Producer's Monetary Loss Function depicted in USAF R&M 2000 Process is, in essence, Taguchi's Loss Function. Lastly, the researcher included Troubleshooting Techniques such as Process Flowcharts, Cause and Effect Diagrams, and Pareto Analysis as these are extremely valuable methods in problem solving and identifying areas where VRP application would be most useful.

Measuring the Effects of VRP

Because VRP encompasses such a broad spectrum of methodologies, to precisely answer this investigative question, the researcher separated the methodologies into two categories. These categories emerged from Crosby's "Cost of Quality" measurements of appraisal costs (or on-line quality control methods) and prevention costs (or off-line quality control methods). Interestingly, Crosby's Cost of Quality measurements and Sullivan's perspective of Total Quality Control stages were quite similar.

Appraisal costs or on-line quality control methods such as Statistical Process Control provide the most quantifiable measure of VRP. By taking a before and after snapshot of the process and products produced by the process, the results of applying on-line quality control measures can clearly be seen as shown by the F100 turbine blade grinding process. Prior to SPC, the distribution of critical part characteristics exceeded the upper specification limit of 80.93 resulting in a rework rate of 3.2 percent. After applying SPC techniques

to remove the causes of variation, manufacturing variability was reduced and no rework was required. This eliminated wasting money in the "hidden factory" to rework scrap and the necessity of having to do it again a second time.

The effects of VRP can also be measured by prevention costs derived from off-line quality control methods. For example, Aerojet Ordnance used Design of Experiments and Parameter Design to improve the manufacturing process used in producing the ADAM mine. Prior to using VRP, nineteen out of twenty-five lots were rejected although SPC was in use and twelve of thirteen processes were within their tolerances. Applying a Taguchi experiment to identify critical parameters, the thirteen parameters used in SPC were tested at three different levels. Conducting only twenty-seven experiments, firing six rounds each, revealed four parameters to be critical. Setting these four parameters at their best levels, the process yielded good lots without any rejects. The other nine parameters were deemed less important and their tolerances were relaxed. The effects of VRP for Aerojet Ordnance resulted in meeting production schedule while achieving significant cost savings.

An important lesson to be learned from the Aerojet Ordnance success story is that VRP methods in themselves did not guarantee quality. Although SPC was used, it was necessary to apply a Taguchi experiment to identify critical parameters to eliminate defective production. In this case,

a combination of VRP methodologies was required to ensure quality. Thus, the appropriate selection of methodologies, or combinations thereof, is imperative to successful Variability Reduction.

On a broader scope, the effects of VRP can be measured in terms of the number of design and redesign changes, the time required to field a system, the number of defects produced, and costs associated with rework, scrap, system failure, and warranty action. From an Air Force point of view, the extraordinary amount of time from concept exploration to Initial Operational Capability is a critical concern. Similarly, the hundreds of design changes, costs of defects, and product performance agreements are also of paramount concern to Air Force leaders. Thus, VRP is one of the most important actions the Air Force can take to improve the combat capability of new or modified systems. Additional benefits may include improved reliability, better maintainability, improved mobility, reduced manpower requirements, and lower life cycle costs. For example, by using VRP methodologies to enhance reliability and maintainability, VRP can contribute to increased combat capability. The importance of enhanced R&M obtainable through VRP is shown in the "USAF High Reliability (HI-REL) Fighter Concept Investigative Study," where enhanced R&M was responsible for a 146 percent increase in targets killed, a

125 percent increase in daily sortie rate, and a reduction of 72 percent in combat downtime over a 30 day war simulation.

Other Findings

Although not directly addressed in the research or investigative questions, the research revealed some other important applications for VRP within the R&M 2000 Process.

Motivation. Motivation is an R&M 2000 principle. Motivation is the perfect vehicle to activate commitment to VRP from the defense industry through source selection, incentives, and evaluation of VRP progress throughout a program. By isolating VRP as an important technical factor to be monitored throughout a program, it can be used to evaluate the technical design proficiency of a company as well as estimate a company's capability to produce a quality product--a product with enhanced reliability and maintainability characteristics.

Incentives. Rewarding successful applications of VRP and striving for continuous improvement can also be used as an incentive to contractors. Moreover, progress in VRP achievement provides a quantifiable method towards evaluating certain aspects within a program. Additionally, adherence to VRP principles resulting in enhanced reliability and maintainability of a system could be used as quantifiable evidence towards justifying the award of a blue ribbon rating for a contractor.

Clear Requirements. Customer requirements, when translated into design and manufacturing specifications, can be classified as target values (or ideal values) for reliable performance in the user's operational environment. Examples of target values are a Statement of Operational Need (SON) requirement for bombing accuracy; a manufacturing specification for surface flatness; and a performance standard for specific fuel consumption. Therefore, Air Force managers responsible for writing SON's, manufacturing specifications, and performance standards should understand Variability Reduction methodologies. Understanding the methodologies involved in VRP can enhance the horizontal communication and overall information exchange between Air Force managers and defense industry contractors responsible for producing Air Force systems making the acquisition process a team effort. For these reasons, it is important Variability Reduction methodologies be understood by Air Force personnel in the chain of program responsibility from the Program Manager and Contracting Officer to the Engineer and Line Manager.

Summary

VRP methodologies are useful to Air Force personnel involved in the acquisition process. Variability Reduction is not only important in developing new systems but is useful throughout a system's life cycle as VRP can be applied to modifications and upgrades to existing systems. Improved

performance at reduced costs is the result of reducing the variability around a target value. Variability Reduction also contributes to decreasing the development time for new systems, reducing costs and time spent on design-redesign, and eliminates waste in manufacturing operations, system support, and service use.

If Air Force managers involved in the acquisition process understand the techniques used in Variability Reduction, they will be better able to exploit the benefits obtained from their use. The resultant outcomes could be extremely beneficial to the Air Force--more efficient managers producing more effective and supportable systems at reduced costs.

IV. Conclusions and Recommendations

Overview

The purpose of this chapter is to provide an overview of the entire research project stressing the role of Variability Reduction in the acquisition process. The first section summarizes the primary objective of the research effort and the methodology followed to achieve the objective. The second section summarizes the role of VRP in the Air Force. Finally, the chapter concludes with recommendations for further research.

Summary of the Research Effort

This section briefly summarizes the research objective. Then, a synopsis of the methodology followed to achieve that objective is provided.

Research Objective. The objective of the research was to develop a Variability Reduction Process Handbook to provide a source document to enhance the understanding of Variability Reduction methodologies. The handbook will provide Air Force managers a consolidated source of information pertaining to the Variability Reduction Process. The handbook addresses proven management methods that, when properly applied, contribute to Variability Reduction. The purpose of the handbook is **not** to produce expert statisticians, but to present Variability Reduction concepts

in an understandable manner to expose Air Force managers to methodologies used in Variability Reduction.

It is important for Air Force personnel in the acquisition commands to understand that Variability Reduction shortens product development time, reduces design and redesign costs, and eliminates waste in manufacturing operations ultimately producing a robust product--a product that is insensitive to physical and functional variation. This, in turn, increases combat capability by producing more reliable and maintainable systems requiring less support in terms of mobility and manpower requirements while simultaneously reducing acquisition time and costs.

Research Methodology. The methodology undertaken during the conduct of this research consisted of first, identifying official guidelines and directives addressing Variability Reduction and then identifying Variability Reduction methods applicable to the acquisition of Air Force systems. After identifying the Variability Reduction methods to be included in the handbook, a comprehensive literature review surveyed these methodologies. The ensuing step consisted of transforming rather complex concepts within these methodologies into "layman's terms." The handbook had to be understandable to be effective. Then, the Variability Reduction Process Handbook was sent to HQ USAF/LE-RD for final evaluation and validation, and finally for

dissemination, in whole or in part with the contracted version of the Variability Reduction Process Guidebook.

The Role of VRP in the Air Force

In October, 1987, HQ USAF, Office of the Special Assistant for R&M in Washington, D.C., published the USAF R&M 2000 Process to provide guidance for achieving increased combat capability through enhanced R&M practices. The R&M 2000 Variability Reduction Process is one of the building blocks of the R&M 2000 Process and advocates improving combat capability by increasing reliability and reducing costs. VRP is a method of improving the combat capability of Air Force systems while simultaneously reducing costs and decreasing the development time required to field a new system. Producing robust designs makes product performance insensitive to variations caused by the manufacturing process, the environment, and customer use. Reducing variability around a target value and then producing these products under capable manufacturing processes will improve the quality of Air Force systems. Implementing Variability Reduction techniques will reduce design and redesign efforts eliminating waste in manufacturing and service use. Variability Reduction is a means to increase combat capability by meeting customer expectations in minimum time at the lowest possible cost. The importance of VRP is that it is the initial link in a chain of events leading to the achievement of R&M 2000 goals.

Variability Reduction applies to selected phases within a system's life cycle and makes two seemingly contradictory goals compatible--the goals of fielding highly reliable and maintainable systems while decreasing development time and reducing production and operational costs.

Variability Reduction stresses uniformity around a target value rather than conformance to specification limits. Robust designs make a product insensitive to noises, thus improving functional performance and reliability. In an era of tightening fiscal constraints, Variability Reduction can be an extremely valuable tool in acquiring "more bang for the buck." However, to derive maximum benefit from this tool, Air Force managers must be aware of its capabilities and methodologies.

Reducing variability around a target (or best) value is a means of improving quality, reliability, and maintainability of Air Force systems at reduced costs by eliminating performance variations in products caused either by design or manufacturing processes. VRP is a useful tool applicable throughout a system's life cycle up to disposal. However, application of VRP techniques are best employed during the development, design, and production stages because these are the stages where the decisions made have the greatest impact on the performance, reliability, maintainability, and supportability of the system. Implementing VRP in this "window of opportunity" will not

only enhance performance characteristics and overall system supportability but can significantly decrease total life cycle cost as well.

VRP methodologies are the first step towards increasing combat capability by producing more reliable and maintainable systems requiring less support in terms of mobility and manpower requirements while simultaneously reducing acquisition time and costs.

Recommendations for Future Research

In developing the handbook, several possibilities for future research emerged. Potential areas warranting further investigation include:

1. How to incorporate Variability Reduction requirements into Statements of Work and Requests for Proposal.
2. The feasibility of inserting Variability Reduction clauses in contracts.
3. The significance of providing monetary incentives to contractors in exchange for enhanced R&M through VRP.
4. Investigating the role of VRP in source selection.
5. Measuring enhanced R&M through VRP as contributing criteria to awarding blue ribbon ratings to contractors.
6. VRP applications for depot level maintenance and repair activities at Air Logistic Centers.

In conclusion, the purpose of this thesis was to produce a handbook that would expose Air Force managers to the methodologies involved in Variability Reduction. The handbook attempts to transform and present some complex concepts in as simplistic a manner as possible. The handbook is not meant to be an all inclusive document or the final word on Variability Reduction. There is much to be gained from this R&M 2000 building block and there are still many areas requiring work towards making VRP a standard operating procedure in the acquisition process. The Variability Reduction Process is an important part of the Total Quality Management initiative and R&M 2000 Process. VRP and its application to the Air Force acquisition process will yield large dividends by producing "Quality" systems for the United States Air Force.

Appendix A: Policy Letter #6: R&M 2000 Variability Reduction

DEPARTMENT OF THE AIR FORCE
OFFICE OF THE CHIEF OF STAFF
UNITED STATES AIR FORCE
WASHINGTON, D.C. 20330

14 JUL 1988

REPLY TO ATTN OF: CV

SUBJECT: Policy Letter #6: R&M 2000 Variability Reduction

TO: ALMAJCOM-SOA/CC

1. The variability reduction process is a methodology to improve quality, reliability, and maintainability of Air Force systems at reduced costs. It tries to eliminate performance variations in products caused by design and manufacturing practices. Traditionally weapon systems have been designed and built to a set of specifications. Variability reduction replaces the specification limits with a single optimum performance value. The result is improved combat capability through more reliable, defect-free weapon systems which do the job they were built for. This process also reduces acquisition time and costs. Since the products manufactured contain fewer defects, warranty and rework costs are reduced. Attachment 1 gives background on the concept.

2. Accordingly, to drive maximum benefit from the variability reduction process, acquisition commands should:

a. Ensure validated user requirements are the basis for all actions.

b. Develop new systems or modifications/upgrades to existing systems simultaneously with their production processes. Ensure that the product and the process are as fully integrated as possible to meet user requirements at the lowest possible cost. Evaluate progress in this area during each design review.

c. Reduce performance variations in both the product and the manufacturing process until reaching the most cost-effective level. Assess cost-effectiveness using the monetary loss function which is notionally explained at attachment 2.

d. Conduct training in variability reduction concepts and techniques for personnel working in acquisition and repair activities.

3. This policy applies to acquisition and post-production support of all Air Force systems, subsystems, and equipment. All commands involved in acquisition should achieve the policy objectives by 1993. Identify education and training requirements to appropriate agencies for the FY92-96 POM. ATC, AU, and AFA will plan, program, and administer education and training to support command requirements. Please send outlines of your strategies to SAF/AQ and AF/LE by January, 1989.

Monroe W. Hatch Jr.
MONROE W. HATCH, JR
General, USAF
Vice Chief of Staff

2 Atch
1. "The USAF R&M 2000 VRP"
2. Monetary Loss Function

VARIABILITY

REDUCTION

PROCESS

HANDBOOK

VARIABILITY REDUCTION PROCESS HANDBOOK

TABLE OF CONTENTS

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FIGURES

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Introduction

Success of the United States defense posture depends on countering a numerically superior enemy by employing qualitatively superior weapon systems--weapon systems that **must sustain operational performance over time.** Highly reliable and maintainable systems are critical variables in the equation of successfully engaging and defeating a numerically superior enemy. With a clear focus on maximizing resources, key concerns are optimizing quality and enhancing reliability and maintainability. Consequently, the effective and efficient use of resources along the path from the "drawing board" to the "flight line" has never been more essential.

Variability reduction is a viable method for improving the quality, reliability, and maintainability of Air Force systems. Thus, it is important for Air Force managers to understand the principles behind this concept.

Policy Letter #6: R&M Variability Reduction establishes Air Force policy for Variability reduction to improve the quality, reliability, and maintainability of Air Force systems at reduced costs. This policy letter directs acquisition commands to derive maximum benefit from the variability reduction process by achieving the following objectives by 1993:

a. Ensure validated user requirements are the basis for all actions.
b. Develop new systems or modifications/upgrades to existing systems simultaneously with their production processes. Ensure that the product and the process are as fully integrated as possible to meet user requirements at the lowest possible cost. Evaluate progress in this area during each design review.
c. Reduce performance variations in both the product and the manufacturing process until reaching the most cost-effective level. Assess cost effectiveness using the monetary loss function.
d. Conduct training in variability reduction concepts and techniques for personnel working in acquisition and repair activities. (General Hatch, 1988)

This policy applies to acquisition and post-production support of all Air Force systems, subsystems, and equipment. The purpose of the Variability Reduction Program is to improve combat capability by producing more reliable, maintainable, and defect free weapon systems. Since the products manufactured contain fewer defects, warranty and rework costs are reduced decreasing acquisition time and total life cycle costs.

Overview

The purpose of this Variability Reduction Process (VRP) handbook is to provide a source document to explain the methodologies involved in variability reduction.

VRP is a means to improve quality, reliability, and maintainability of Air Force systems at reduced costs by eliminating product performance variations caused either by design or manufacturing processes.

Reducing variability around a target (or best) value shortens product development time, reduces design and redesign costs, eliminates waste in manufacturing operations ultimately producing a robust product--a product that is insensitive to functional variation. This in turn increases combat capability by producing more reliable and maintainable systems while simultaneously reducing acquisition time and costs.

As depicted in Figure 1, the essence of variability reduction is to reduce variability around a target value and not just conform to specification limits.

VARIABILITY REDUCTION APPROACH - DESIGN AND BUILD TO TARGET VALUES, NOT SPECIFICATION LIMITS

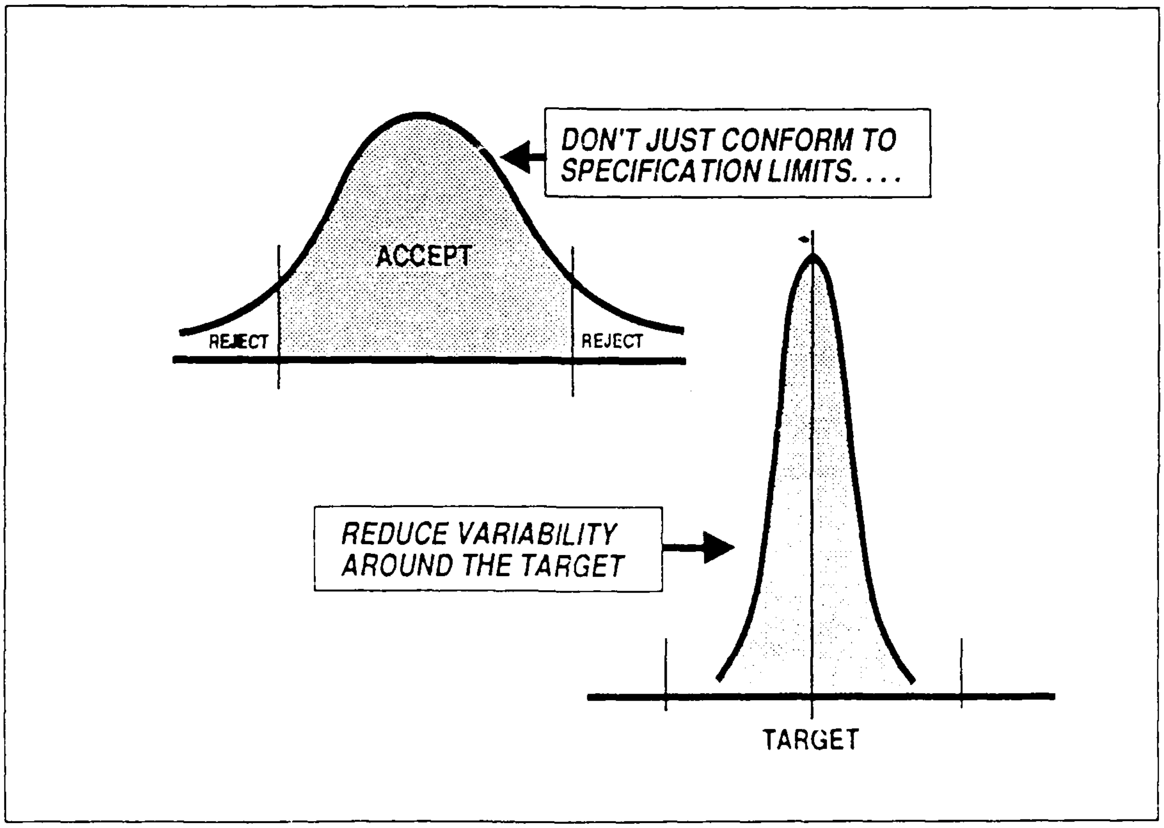


Figure 1. The Variability Reduction Approach
(Source: USAF R&M 2000 Process, 93, 1987)

Total Quality Management (TQM) is a managerial process directed at establishing continuous improvement in all DoD activities. TQM strategy emphasizes doing the right thing, right the first time, on time, all the time while continuously striving for improvement and always satisfying the customer. TQM consists of continuous process improvement activities involving everyone in an organization--managers and workers--in an integrated effort toward improving performance at every level. TQM integrates fundamental management techniques, existing improvement efforts, and technical tools under a disciplined approach focused on continuous process improvement. The activities are ultimately focused on increased customer/user satisfaction. As shown in Figure 2, VRP is a shared element of both TQM and the R&M 2000 Process.

R&M 2000 Process operational goals advocate, as a corollary to performance, increased combat capability, decreased vulnerability of the combat support structure, decreased mobility requirements per unit, decreased manpower requirements per unit of output, and decreased costs. Achieving these goals will reduce the life cycle costs of systems, reduce systems' dependency on spare parts, require fewer combat support personnel, and result in more missions per deployed system. Enhanced reliability and maintainability in our weapon systems and related support systems will not only increase our combat capability but will save valuable resources as well.

The R&M 2000 principles are the basic tenets of the R&M 2000 Process. The R&M 2000 principle called Preservation directs aggressive action be taken to ensure inherent Reliability and Maintainability are preserved during production and sustained in the operational environment. Preservation stands for the preservation of the design during manufacturing, fielding, and repair. Preservation also advocates that feedback be used to continually improve products and processes. Variability Reduction is one tool for achieving the goals of preservation.

The R&M 2000 Variability Reduction Process is an R&M 2000 building block whose purpose is to improve the R&M of Air Force systems while simultaneously reducing costs. The strategy of VRP is to adopt within the Air Force and the defense industry, a modern concept of design and manufacturing excellence eliminating poor design and manufacturing processes that produce unreliable equipment that is both difficult and costly to maintain. The purpose of VRP is to produce a product that is insensitive to physical and functional variation due to manufacturing, the environment, and operational use. As such, VRP addresses the causes of the problem, not just the symptoms. Reducing variability around a preestablished target value diminishes product development time, reduces design and redesign costs, and eliminates waste in manufacturing operations, system support, and service use.

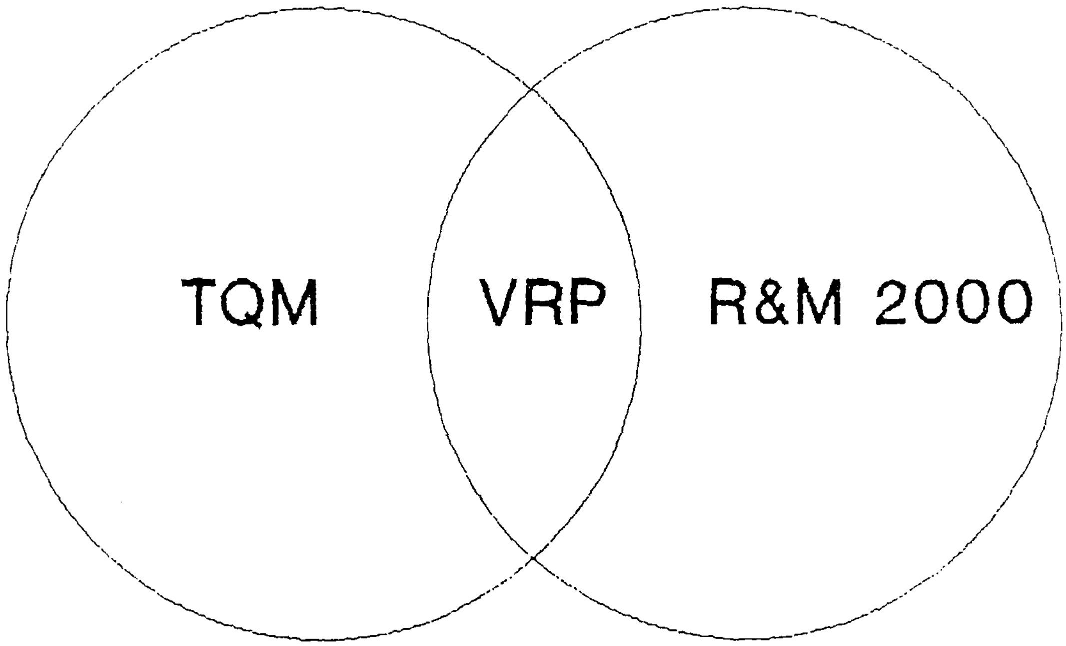


Figure 2. Relationship Between TQM, R&M 2000, and VRP

Variability Reduction

The R&M 2000 Process addresses six methods for reducing variability as illustrated in Figure 3.

Teamwork, Design of Experiments, and the Loss Function are used throughout the acquisition process.

Quality Function Deployment and Parameter Design are applied in the design and development phases.

In addition, Statistical Process Control is used to detect and reduce variation during production.

VRP is a means for improving the combat capability of Air Force systems while simultaneously reducing development time and costs. The purpose of VRP is to meet customer expectations in minimum time at lowest cost. To accomplish this purpose, it is necessary to design robust systems, produce these systems with capable manufacturing processes, and continuously improve both the product and its processes.

Robust Designs: Designs that are insensitive to manufacturing and operational influences.

Capable Manufacturing Processes: Processes which produce uniform, defect-free products.

Continuous Improvement: Improvement in all processes throughout the life of the system.

TOOLS	R&M 2000 VRP		
	ROBUST DESIGN	CAPABLE PROCESSES	CONTINUOUS IMPROVEMENT
TEAMWORK	X	X	X
QUALITY FUNCTION DEPLOYMENT (QFD)	X		X
DESIGN OF EXPERIMENTS (DOE)	X	X	X
PARAMETER DESIGN	X		X
PROBLEM ANALYSIS TECHNIQUES	X	X	X
STATISTICAL PROCESS CONTROL (SPC)		X	X

Figure 3. VRP Tools
(Source: HQ USAF/LE-RD, 1989)

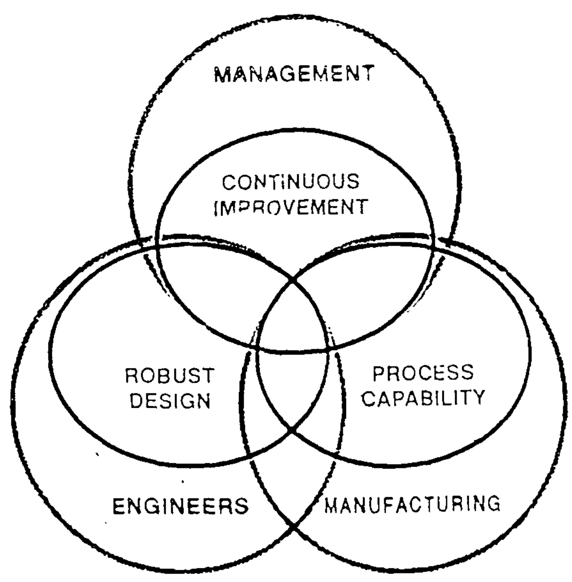


Figure 4. VRP Techniques
(Source: HQ USAF/LE-RD, 1989)

Teamwork is a process whose purpose is to ensure that all personnel representing functions relevant to the total project are made active participants from the start. These functions include design, quality manufacturing, operations, and outside suppliers working cooperatively with maximum information exchange, to improve products, processes, and services.

Teamwork is the process where performance, reliability, maintainability, supportability, and producibility are all considered concurrently. The team approach helps ensure that all decisions made at each decision point are based on total product knowledge.

Team building includes, but is not limited to, the assignment of people to mutltifunctional management teams, interdisciplinary design teams, process improvement teams, and quality circles.

An important application of the team approach is in the product and process design effort, where representatives of all disciplines and functional areas are brought together at the start of a project. Coordinating and integrating the contributions of these people require cooperation and continuous communication. Computer-aided engineering (CAE) represents an excellent way of enhancing the interaction between various functions of the product development team. This interacting team design approach has proven to be superior to the sequential design practice used in the past (*VRP Guidebook*, 1989:13,B-2).

Design of Experiments

Design of Experiments is a robust technique valuable in resolving complex problems--improving both product designs and manufacturing processes. DOE's objectives are to identify critical parameters, isolate the causes of variation, and improve technical or operational characteristics enhancing quality and fitness for use. The experimental results provide a better understanding of the process and can be used to conduct parameter design. Parameter design, a logical continuation of DOE, is a technique used to analyze the experimental data ultimately yielding robust designs by selecting the optimum product and process parameters that minimize variability and provide better performance over a wider range of operating conditions and environments (VRP Guidebook, 1989:14).

PURPOSE: MEET CUSTOMER EXPECTATIONS, IN MINIMUM TIME, AT LOWEST COST

OBJECTIVES	ROBUST DESIGN	PROCESS CAPABILITY	CONTINUOUS IMPROVEMENT
PRIMARY RESPONSIBILITY	ENGINEERS	MANUFACTURING	MANAGEMENT
TEAM	INTERDISCIPLINARY	IMPROVEMENT	MULTI-FUNCTIONAL
TOOLS / TECHNOLOGIES	QFD / DOE / PARAMETER DESIGN	DOE / SPC	LOSS FUNCTION

Figure 5. VRP Elements
(Source: HQ USAF/LE-RD, 1989)

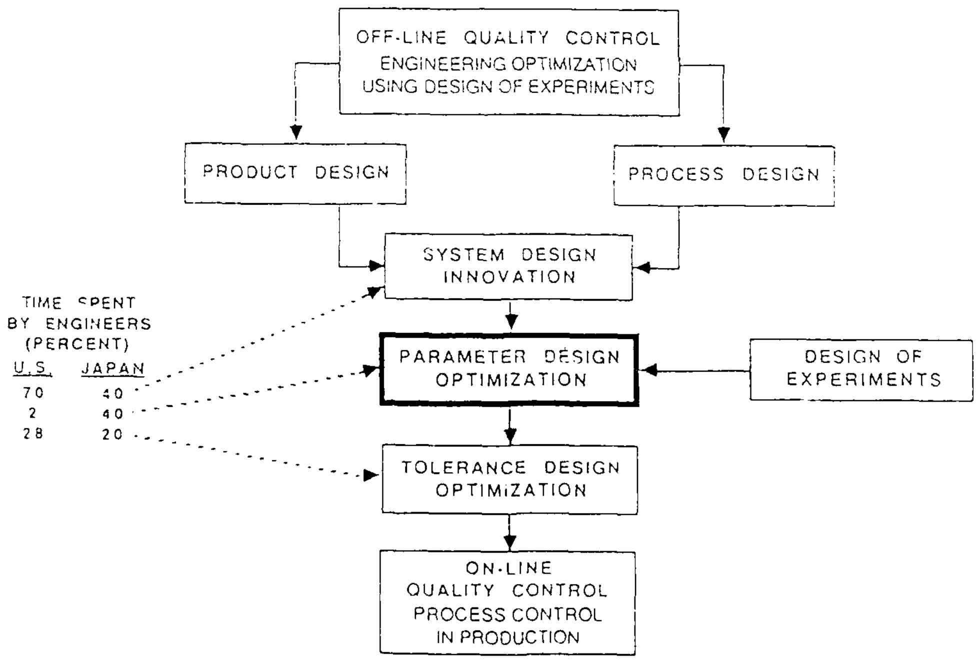


Figure 6. Quality Control Steps
(Source: VRP Draft, 1989:B-15a)

Taguchi Methods

Genichi Taguchi is a Japanese statistician and engineer whose quality techniques, methodologies, and philosophies have had a major impact on America's quality perspective.

Taguchi views quality in terms of "loss to society." Taguchi looks at quality not in terms of value added but in terms of "**the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions**" (Taguchi, 1985:7). Within this context of quality, Taguchi restricts loss to two categories:

1. Loss caused by variability of function
2. Loss caused by harmful side effects (Taguchi, 1985:7).

Whereas much emphasis has been placed on Taguchi's statistical techniques, the locus of his message centers on the conceptual framework of the quality improvement process. When approached from this perspe. ve, two fundamental concepts provide the basis for Taguchi's principles.

1. Quality losses must be defined as deviation from target, not conformance to arbitrary specifications;

2. Achieving high system quality levels economically requires quality to be **designed in.** Quality cannot be achieved economically through inspection and product screening.

   The three stages of quality by design are:

   a. Systems (functional) design;
   b. Parameter (targeting) design;
   c. Allowance (tolerance) design.

   Systems and parameter design provide the greatest opportunity for quality cost reduction; allowance design often entails increased costs to achieve higher quality (Gunter, 1987:44).

As a product deviates from its design target, quality deteriorates and the costs of rework and scrap encountered in the "hidden factory" rapidly accumulate, continuously increasing as the product progresses through each phase of the manufacturing cycle. Therefore, it is more efficient to design in quality than to try to inspect in quality. It is extremely costly to re-engineer a poor design after production has started or even worse, after the product reaches the customer.

The Taguchi Loss Function

The essence of Taguchi Methods involves a concept called the quality loss function--a method of quantifying product and process quality (in terms of dollars). Understanding the quality loss function is vital to understanding Taguchi's Methods. The concept is predicated on 200-year-old mathematical foundations of statistics established by Gauss and has been a focal point for statistical decision theory over the last 40 years.

The way the loss function is established is determined by the type of quality characteristic. A quality characteristic is how performance (quality) is measured. There are five types of quality characteristics:

1. A Nominal Value is Best.
   (Achieving a desired target value with minimal variation).
   For example, output voltage, dimension.

2. The Smaller the Better.
   (Minimizing a response).
   For example, friction, shrinkage, wear.

3. The Larger the Better.
   (Maximizing a response).
   For example, tensile strength

4. Attribute.
   (Classifying and/or counting data).
   For example, appearance.

5. Dynamic.
   (Response varies depending on input).
   For example, the fan drive speed should vary depending on the temperature of the automotive engine.

Many organizations have adopted the loss function focusing on measurable quantities such as scrap, rework, warranty costs, non-manufacturing workload due to un-quality, excess flow times and inventory, extra capital investment, market share, customer dissatisfaction, safety and liability (Johnson, 1989).

A "Nominal Value is Best" characteristic will be examined to illustrate the loss function.

Simplistically, the concept can best be illustrated by points along a quadratic curve. As these points deviate farther away from the target value on the curve, an associated loss of quality accompanies this deviation.

A key concept of Taguchi's Loss Function is that a product does not start causing losses only when it is out of specification, but causes a loss whenever there is any deviation from the target value.

As depicted in Figure 7, a central target (T) represents the ideal state of the design parameter (or ideal target value). Specification limits (S), denoted by T + S and T - S represent standard symmetric upper and lower specification limits. The vertical axis measures value lost due to deviation away from the ideal target value.

This basic explanation of Taguchi's loss function is indeed an oversimplification. Ideal target values and specification limits are necessary entities of the concept and setting the values associated with these entities are as important as the concept itself. Moreover, as the measure of quality deviates from its ideal target value, there is no instantaneous change from perfect to useless at some arbitrary point. Instead, there exists a gradual deterioration of performance as the quality measure shifts away from the target value. In fact, deterioration can continue even beyond the specification limits. Greater than 100 per cent losses beyond the totality of individual value can occur when poor performance of a single component within an assembly results in the destruction of the entire assembly. In reality, the precise shape of the loss function curve illustrated in Figure 7 is extremely difficult if not impossible to calculate. However, good approximations of the curve can prove to be very useful (Gunter, 1987:45).

Within the context of Taguchi's Loss Function, it is important to comprehend how value is defined. It is not merely on a scale of 0 per cent (no value lost) to 100 per cent (all value lost). Taguchi defines lost value in terms of "the losses a product imparts to the society from the time a product is shipped" (Taguchi and Wu, 1980). From this definition, the customer oriented emphasis that Taguchi places on quality can clearly be seen (Gunter, 1985:45).

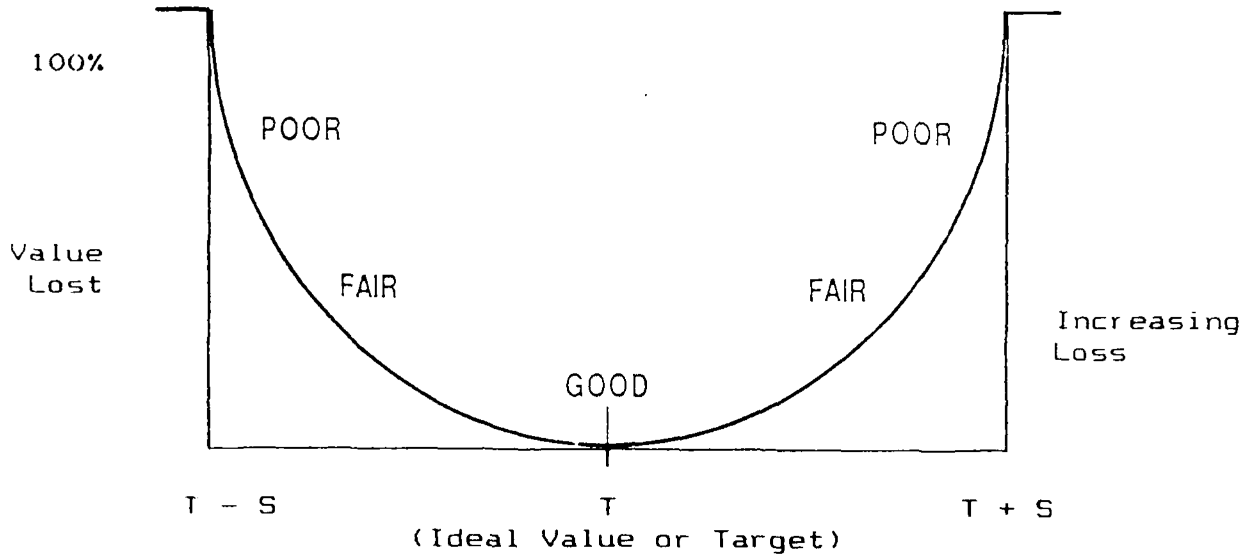


Figure 7. The Loss Function

Since Taguchi's approach to quality emphasizes that quality losses begin whenever there is any deviation from the target value, quality is best achieved by minimizing variance, rather than by strict conformance to specification.

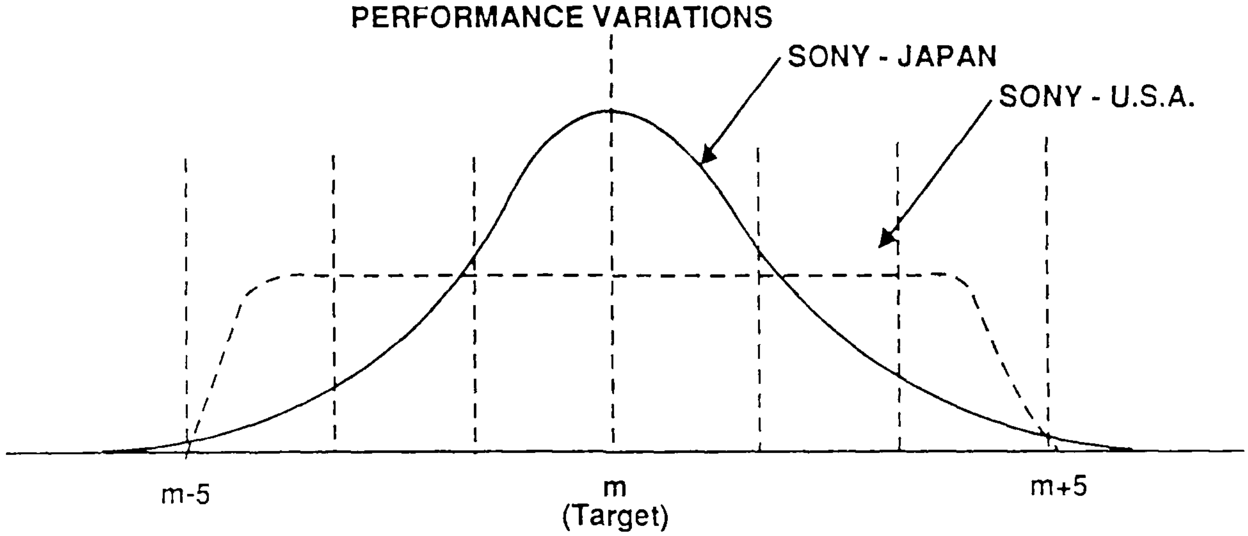
Comparison of Japanese and American built Sony television sets is a classic example of this philosophy. In 1979, an article appeared in the Asahi (a Japanese newspaper) addressing American consumer preference for Sony televisions built in Japan over the U.S. The Sony televisions had been manufactured in two plants using identical designs and tolerances. One plant was located in Tokyo, Japan and an identical subsidiary plant had been built by Sony in San Diego, California. Even though the U.S. plant produced sets that were defect free (i.e. no sets were produced with out-of-tolerance color density) and the Japanese plant produced televisions with a defect rate of 3 per 1,000 units (color density out-of-tolerance in 3 out of 1,000 sets), the American consumer preferred the Sony televisions built in Japan.

Japanese built Sonys were perceived as having better quality than the sets built in the U.S. because the color density of the Japanese sets was closer to the target value (despite having 3 defects per 1,000). Although Japanese and American made televisions were manufactured to identical tolerances, customers were clearly able to see the difference produced by variability reduction.

Thus, tolerances alone do not ensure quality. They merely dictate the limits of product functionality. As was illustrated by the Sony televisions, two products can both function within identical specifications but one can still be superior relative to the other.

Manufacturing every product exactly to desired nominals is essential to ensure quality. This is an important aspect of Variability Reduction.

DIFFERENCE IN PRODUCTION QUALITY BETWEEN JAPAN AND USA



DISTRIBUTION OF COLOR DENSITY IN TV SETS

SPECIFICATION: m $\pm$ 5

TYPES OF DISTRIBUTION

SONY CASE CITED FROM THE ASAHI, APRIL 17, 1979

FACTORY LOCATION	APPROX. TYPE OF DISTRIBUTION	PERCENT DEFECTIVE
SAN DIEGO	UNIFORM	ALMOST ZERO
JAPAN	NORMAL	0.3%

Figure 8. Difference in Sony Production Quality Between Japan and the United States (Source: ASI, 1988:II-5)

The Loss Function

$$\text{Loss} = C(S^2+(\bar{x} - T)^2)$$

where:

C = Cost Constant

S^2 = Variance

$\bar{x}$ = Average

T = Target

Mathematically, the loss function can be represented by an equation that includes a cost constant which is based on costs and specification limits, the variance which measures the variability or spread of a distribution, and the desired target. By reducing the variance and staying close to the target value, losses for a given cost constant can be reduced.

Prior to production, off-line quality engineering should reduce variance through design and establish the design target for the lowest loss. Taguchi Methods, design of experiments, and Quality Function Deployment are complementary tools that should be applied during the off-line phase of a product or process life cycle (Ross, 1988:41-43).

PRODUCER'S MONETARY LOSS FUNCTION

These are special cases of the monetary loss function to determine the producer's loss due to process variability. Loss function theory holds that dollar losses accrue to producers (and ultimately to customers) as produced items vary from design target values. The actual form of the loss function will vary for particular processes, and is best derived from empirical data.

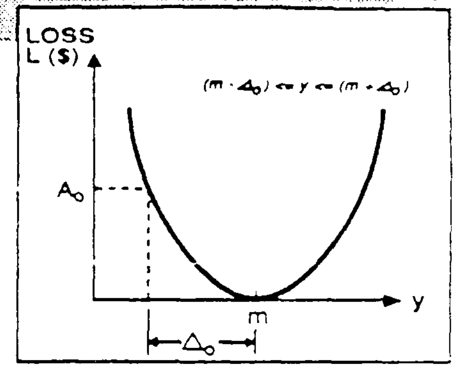
CASE (1): NOMINAL THE BEST

$$L = \begin{cases} k\,(y - m)^2 \\ k\,(SD^2 + (\bar{y} - m)^2) \end{cases} \qquad k = \frac{A_o}{\Delta_o^2}$$

m = design nominal or target value
A_o = dollar loss at the tolerance limit
Δ_o = half the manufacturing tolerance
SD = process standard deviation
$\bar{y}$ = process mean

IF PROCESS CAPABILITY (Cp) IS KNOWN, PROCESS IS SYMMETRICAL & CENTERED, AND (+) AND (-) TOLERANCES EQUAL, THEN THE AVERAGE DOLLAR LOSS PER UNIT IS

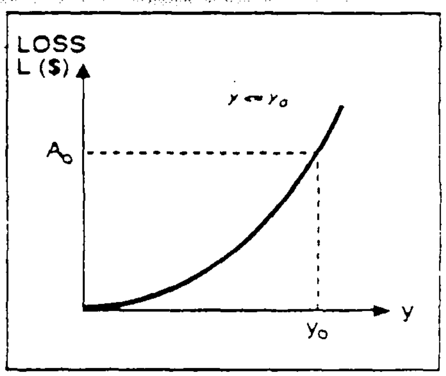
$$L = \frac{A_o}{9 \times Cp^2}$$



CASE (2): SMALLER THE BETTER

$$L = \begin{cases} k\,(y)^2 \\ k\,(\bar{y}^2 + SD^2) \end{cases} \qquad k = \frac{A_o}{y_o^2}$$

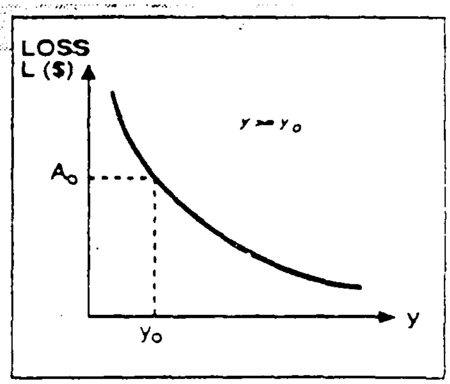
y_o = upper tolerance limit



CASE (3): LARGER THE BETTER

$$L = \begin{cases} k\left(\frac{1}{y^2}\right) \\ k\left(\frac{1}{\bar{y}^2}\left(1 + 3 \times \frac{SD^2}{\bar{y}^2}\right)\right) \end{cases} \qquad k = A_o y_o^2$$

y_o = lower tolerance limit



**NOTES:*
1 The first formula in each set is loss for an individual item; second formula is average loss per unit.
**2 These formulae may be included in standard SPC computer programs to give average loss per unit for each process.*

Figure 9. Producer's Monetary Loss Function
Source: R&M 2000 Process, 1988:94)

Functional Performance

Taguchi's second fundamental concept addresses the importance of economically achieving high quality in terms of consistency of functional performance. To achieve this, the design must be robust to variation caused by materials, manufacturing, and use.

Taguchi segregates the design cycle into three phases. The first is systems design where the fundamental design and engineering concept is established. The second phase is parameter design which establishes design nominals such as target dimensions, material composition, temperatures, voltages, etc. The third phase involves tolerance or allowance design (Gunter, 1987:47). Figure 10 depicts the three phases of the design cycle.

	SYSTEM	PARAMETER	ALLOWANCE
	Set Concept	Set Target	Set Tolerance
through:	-engineering	-engineering -statistical design -sensitivity analysis	-engineering -statistical tolerancing -experimental design

Figure 10. Three Phases of the Design Cycle
(Source: Kackar, 1987:22)

System Design

The initial engineering effort encompasses system design. Application of scientific and engineering knowledge produces a basic functional prototype design. In conjunction with appropriate technologies using engineering modeling and judgment, this design delineates the initial settings of product or process parameters. Understanding the customer's needs and the manufacturing environment are essential to a successful system design phase (Kacker, 1987:68).

Systems Design is a concept-oriented activity involving little or no need for statistical methods. Nevertheless, it is an important stage. It is the stage in which the initial engineering effort attempts to find a good system to perform the function expected from the product. Using an FB-111 as the design prototype to fly a 20-hour bombing mission would be a functional but non-optimum system for the 20-hour mission because of its limited range and refueling requirements. In this case, a B-52 with its longer range would be a more appropriate system--less sensitive to functional variations inherent through the dependency of multiple aerial refuelings.

Knowing the function of the system, the operating environment, and the dependent variables affecting the system are critical facets of efficient system design.

Parameter Design

The goal of Parameter Design is to set product or process parameter values to develop a high performance product which has minimum sensitivity to noise. A Parameter Design experiment typically considers two types of factors--Control Factors and Noise Factors.

Control Factors: factors whose values can be selected and maintained by the experimenter and that are controlled relatively easy such as materials and processing.

Noise Factors: nuisance variables whose values cannot or will not be selected or maintained and are difficult, costly, or impossible to control, such as ambient temperature, humidity, and customer use.

Parameter Design examines the interactions between Control Factors and Noise Factors seeking parameter levels where a characteristic is stable and robust (insensitive to noise).

The purpose of parameter design is to identify product design characteristics that make the product less sensitive to the effects of environmental factors, product deterioration, and manufacturing variations.

Environmental Factors. Environmental factors are conditions that exist in the environment in which the product will be used by the customer, including human variations in operating the product.

Product Deterioration. Product deterioration consists of the changes in product parameters over time from wear and tear on the product during its life cycle.

Manufacturing Variations. Manufacturing variations are the manufacturing conditions that cause product production to deviate from its nominal values (Gitlow, 1989:501).

Environmental factors, product deterioration, and manufacturing variations are three common sources of product variation. They are classified as common sources of variation because they are chronically present and affect product performance.

Introducing countermeasures to reduce controllable sources of variability can optimally be achieved in the product design phase as displayed in Figure 11 (Kacker, 1987:67).

Product development stages where countermeasures against various sources of variation can be designed into the product.

Product Development Stages	Sources of variation		
	Environmental Variables	Product Deterioration	Manufacturing Variations
Product Design	YES	YES	YES
Process Design	NO	NO	YES
Manufacturing	NO	NO	YES

Figure 11. Countering Sources of Variation
(Source: Kacker, 1987:67)

The importance of parameter design can be illustrated by examining the 1980 U.S. attempt to rescue the hostages in Iran. The mission failed because the helicopters participating in the rescue attempt encountered a dust storm. The dust ultimately destroyed the bearings and clogged the helicopter engines. If the helicopters had been robustly designed to withstand severe dust storms, the outcome of the mission may have been different.

It is universally recognized that the field performance of a product is affected by environmental variables (as well as human variations in operation), product deterioration, and manufacturing imperfections. If the helicopters had been designed robustly, environmental factors (the dust) would not have caused product deterioration (failing helicopter engines) and mission outcome could have been different. From this example, it is clear to see why weapon systems must be designed and produced robustly--insensitive to functional and environmental variation. Ultimately, the success or failure of a mission **may** depend on it.

Parameter design is an essential step in achieving robustness and high quality products without increasing cost. The main objective of parameter design is to determine the nominal values for the control factors maximizing product performance with the least sensitivity to noise and to do this at the least cost. In Japan, forty percent of the engineering time is spent on parameter design compared to only 2 percent in the United States (ASI, 1989:VII-11).

The use of DOE and parameter design is growing in the United States. The automobile industry and government contractors are experiencing substantial increases in quality through the use of these tools. Recently, Aerojet Ordnance, a government owned company munitions plant, was experiencing a serious problem in producing the ADAM mine. Although SPC was in use and 12 of 13 processes were within their tolerances, 19 out of 25 lots were rejected. Aerojet Ordinance used a Taguchi experiment to identify the critical parameters. Selecting the 13 parameters used in the SPC program, Aerojet Ordinance tested the parameters at three different levels. Conducting only 27 experiments firing six rounds each, four parameters were determined to be critical. With these parameters set at their best levels, the process yielded good lots without any rejects. The other nine parameters were deemed less important and their tolerances could be relaxed. The results of the experiment--production schedule met while achieving significant cost savings (Johnson, 1989a).

	U.S.	JAPAN
SYSTEM DESIGN	70%	40%
PARAMETER DESIGN	2%	40%
TOLERANCE DESIGN	28%	20%

FIGURE 12. Comparison of Time Spent on Design
By U.S. and Japanese Engineers
(Source: ASI, 1988:VII-11)

The ultimate purpose of parameter design is to produce a robust product or process. Robustness renders a product or process insensitive to the effects of variability or "noises" from the environment, manufacturing processes, and deterioration in use.

To minimize loss, a product must be produced at optimal levels with minimum variation. Noise is a source of variation affecting a product's functional characteristics.

Noise. Noise variables consist of all the factors causing product performance characteristics to deviate from their nominal value or cause a deterioration in actual performance when compared to desired performance.

Sources of noises can be classified into three categories as shown in Figure 13.

Outer Noise: Outer noise (or external sources of noise) are variables external to the product that can affect product performance. Variations in environmental variables such as temperature, humidity, and dust as well as variations in product operation induced by human inputs are examples of outer noise.

Inner Noise: Inner noise (or internal sources of noise) are deviations of actual characteristics of the manufactured product away from its nominal settings. Inner noise may be caused by product deterioration or by imperfections caused by the aging of machinery or tolerances used during processing.
(Kackar, 1985:180).

Between Product Noise: Between product noise results from piece to piece variation caused by manufacturing imperfections.

Noise factors generally cause a product's functional characteristics to deviate from its target value. Controlling noise factors can be extremely costly if not impossible. By selecting values for control factors that make a product or process insensitive to changes from noise factors renders a robust product.

Instead of finding and eliminating the causes of noise factors, the intent is to remove or reduce the impact of the causes. This yields a robust product--a product robust against noise (ASI, 1988:I-32).

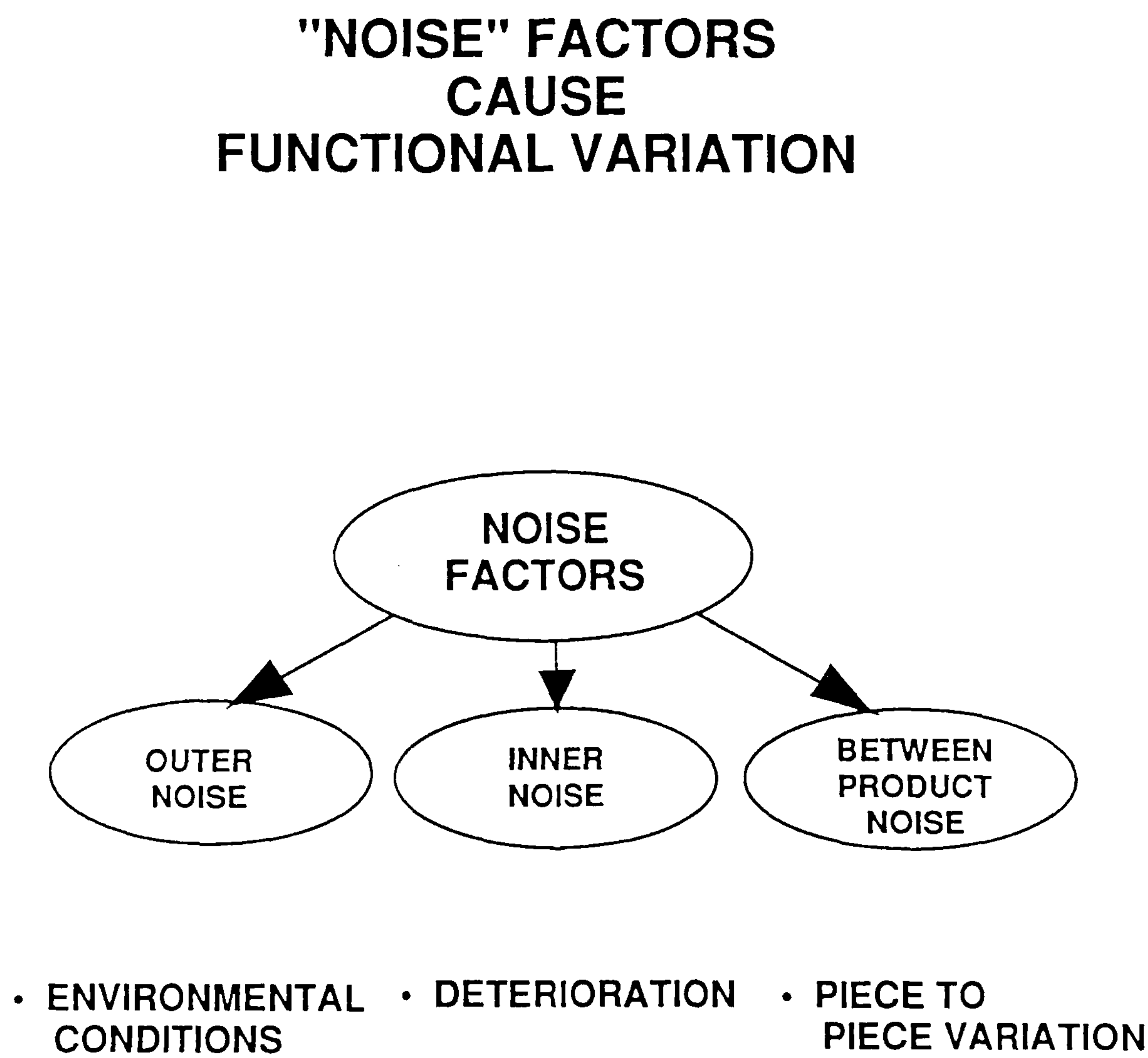


Figure 13. Noise Factors
(Source: ASI, 1988:I-31)

The purpose of a parameter design experiment is to determine the nominal values for design parameter variables that will produce the lowest impact on product performance characteristics by noise variables. These nominal values are established by systematically varying their settings in conjunction with a selected combination of noise variable settings, and then comparing the resultant performance characteristics.

For example, the performance characteristic of interest when considering an electrical circuit design is the output voltage of the electric circuit, y, and its target value, y_0. Assuming the output voltage of the circuit is determined by the gain of transistor X in the circuit, the circuit designer is free to choose the nominal value of this gain.

Since effect of the transistor gain on the output voltage is nonlinear and the circuit designer selects a nominal value of transistor gain to be x_0, an output voltage of y_0 is obtained. If the actual transistor gain deviates from the nominal value of x_0, the output voltage will deviate from y_0 as shown in Figure 14 resulting in a large variation in output voltage. One way of reducing the output variation is to use an expensive transistor whose gain has a very narrow distribution around x_0. However, this is not cost effective.

Another way to reduce output variation is selecting a different value of transistor gain. In this case, if the nominal transistor gain is x_1, the output voltage will have a much smaller variance about y_1. However, the mean value y_1 is far from the target value y_0. Now suppose another component in the circuit, such as a resistor, has a linear effect on the output voltage and the circuit designer is free to choose the nominal value of this component. The circuit designer can then adjust this component to move the mean value of voltage from y_1 to y_0. Adjustment of the mean value of a performance characteristic to its target value is usually a much easier engineering problem than the reduction of performance variation.

When the circuit is designed so that the nominal gain of transistor X is x_1, an inexpensive transistor can be used because having a wide distribution around x_1 results in reduced variability about y_1.

The above example illustrates the concept of exploiting the nonlinear effects of product or process parameters on product performance characteristics. This can be an effective means for reducing the sensitivity of product performance to environmental factors, product deterioration, and manufacturing variations while simultaneously reducing costs (Kackar, 1986:26).

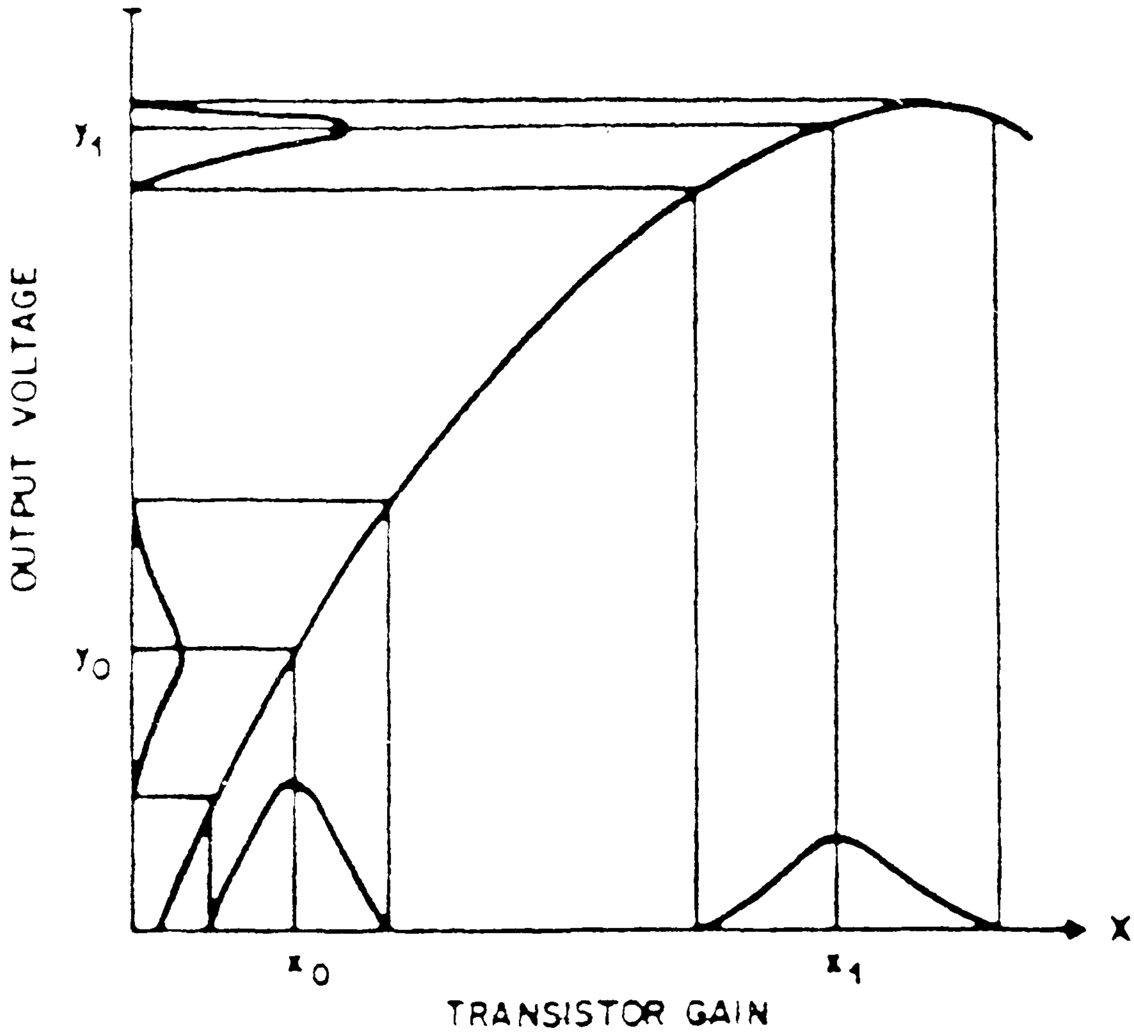


Figure 14. Exploiting Nonlinear Effects of Process or Product Parameters on Product Performance (Source: Kackar, 1986:26)

In reality, it may be impossible to consider every potential noise variable in the parameter design experiment due to the large data requirements. However, the design engineers conducting the parameter design experiment should understand the importance of noise variables and must be constantly wary of potential problems from unknown sources of noise variables (Gitlow, 1989:504).

In conducting the parameter design experiment, the experimenter systematically varies the levels of the most significant noise variables to determine their effects upon the product's performance characteristics. Selecting parameter design variable settings and noise variable settings for a parameter design experiment can become complex. Taguchi devised a procedure for performing the parameter design experiment using a design parameter variable matrix and a noise variable matrix. The design variable matrix lists the design variables in its columns and the appropriate combinations of parameter design variable settings in its rows. Similarly, the noise variable matrix lists the noise variables in its columns and the appropriate combinations of noise variable settings in its rows. The experiment involves conducting tests for every row in the design parameter matrix under the conditions specified in every row of the noise variable matrix. The outcomes (or the resulting performance characteristics) are recorded for each specified combination of design parameter variables and noise variables. Within each configuration of design parameter variables, all the test run settings of the noise variables shown in the noise variable matrix are used to compute a performance statistic. Performance statistics estimate the effects of the noise variables on the performance characteristics for a given design. The setting of the parameter design variables yielding the best performance statistic is selected as the best product design (Gitlow, 1989:505).

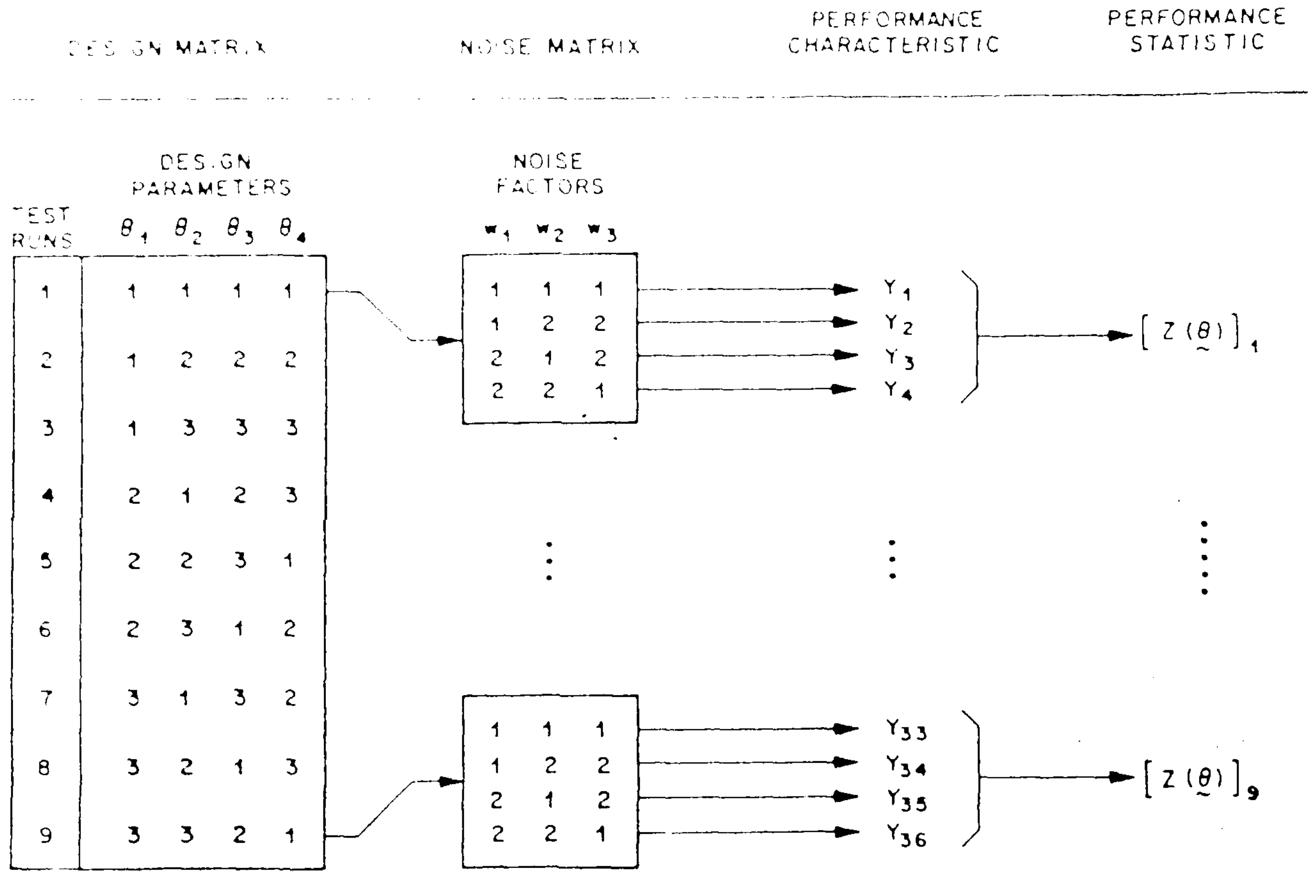


Figure 15. Taguchi-Type Parameter Design Matrix (Source: Kackar, 1986:27)

Taguchi advocates using a performance statistic designated as a signal-to-noise ratio. Three types of signal-to-noise ratios are:

1. The smaller the ratio the better the product design. For example, if friction is the performance characteristic under study, low friction is desirable.

2. The larger the ratio the better the product design. For example, if tensile strength is the performance characteristic under study, high tensile strength is desirable.

3. A nominal value is best. For example, if a gap size specification of 2.255 mm is the performance characteristic under study, a precise gap size of 2.255 mm is most desirable.

Statistically designed experiments using signal-to-noise ratios to evaluate process or product performance can be useful in reducing variation through the appropriate selection of parameter settings. Design parameters for robustness are identified using signal-to-noise ratios.

Tolerance Design

Tolerance Design is the process of specifying tolerances and the nominal settings defined during the parameter design phase. Historically, industry seldomly assigns tolerances scientifically, routinely assigning tolerances by convention. Tolerances that are too narrow result in high manufacturing costs and tolerances that are too wide increase performance variation. Therefore, practical tolerance design necessitates a tradeoff between the customer's loss function and manufacturing costs (Kacker, 1987:69).

Design engineers are forced to use tolerance design when the influences of environmental factors and product deterioration cannot be reduced through parameter design.

Tolerance design should be performed after parameter design because it is less expensive to reduce performance variation through parameter design than it is to control performance variation through the establishment of tolerances. However, having to resort to tolerance design does not force an abandonment of "continuous improvement" as engineers will continuously attempt to produce a better design by establishing nominal values which reduce performance variation (Gitlow, 1989:503).

Quality Function Deployment (QFD) is a methodology developed in Japan to reduce time and decrease costs directly related to new product development while simultaneously improving fitness for use. QFD is a systematic approach for translating users' requirements into product and process characteristics--translating the "Voice of the Customer" into actionable terms within the design or the process.

Within the context of the USAF, the R&M 2000 Process identifies the "Voice of the Customer" as the combat commands' requirements. Therefore, QFD is a technique that identifies customer requirements and provides a discipline to assure that those requirements drive product design and process planning by systematically identifying and exposing necessary considerations that require attention and improvement (Morrell, 1987:1).

As shown in Figure 16, QFD accomplishes this by translating customer requirements into engineering or design guidelines which are then translated into product or part characteristics. These characteristics are, in turn, translated first into process plans and second into specific operations, conditions, or controls. The focus of these transformations is to assure the customer's requirements (i.e. Voice of the Customer) are considered throughout the entire process and ultimately used in designing the final product (Schubert, 1988:132).

As such, QFD is an off-line method to reduce variability in product design while improving the manufacturing process capability of producing uniform, defect-free parts.

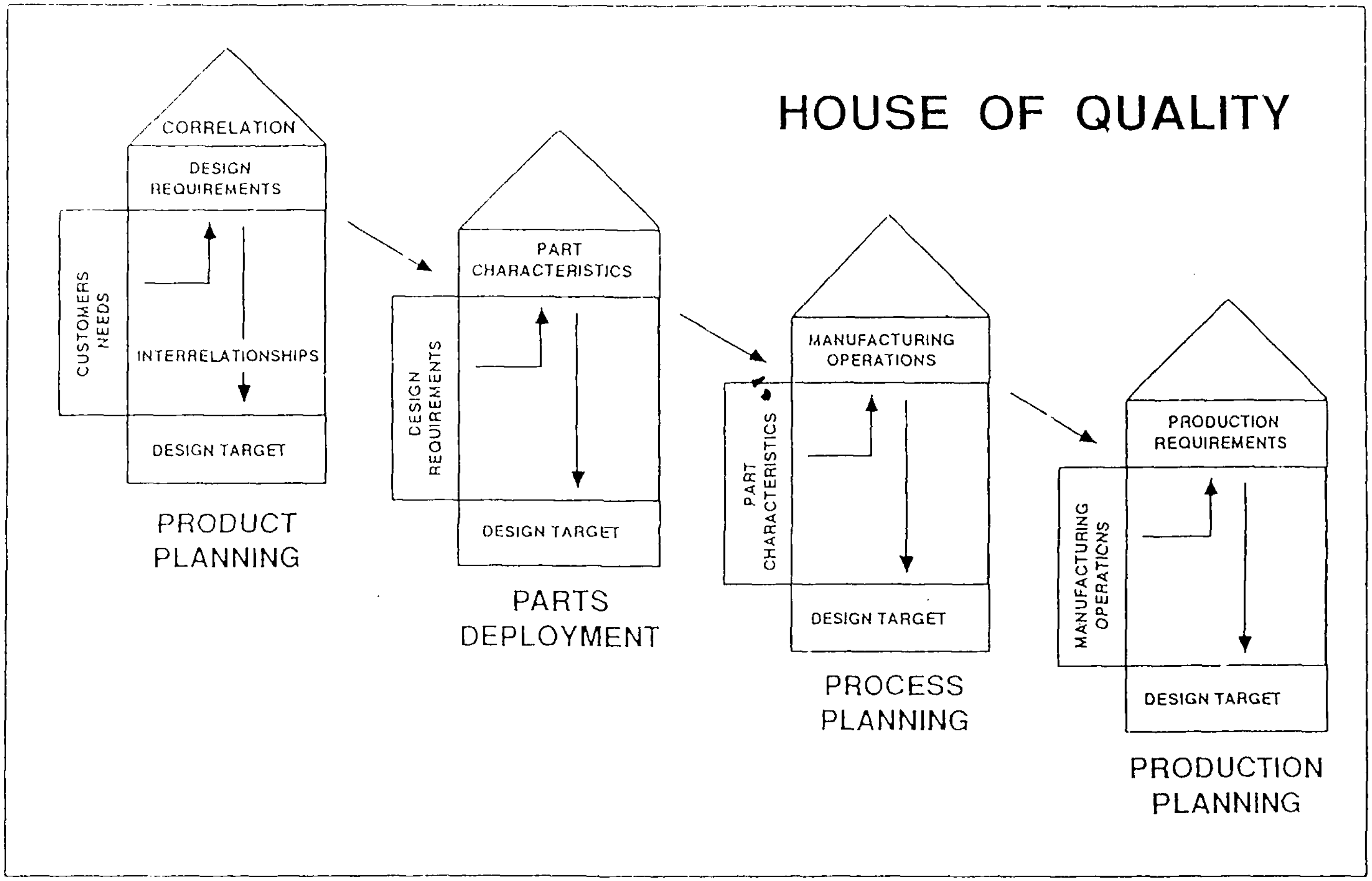


Figure 16

Quality Function Deployment (Source: ASI, 1988)

QFD is a means of transforming the "Voice of the Customer" into design parameters that can be deployed horizontally through product planning, engineering, manufacturing, assembly, and service. Therefore, QFD is a process used to identify conflicting design requirements that must be optimized while recognizing critical quality characteristics that must be controlled.

The overall objective of QFD is to reduce the product development cycle while improving quality and decreasing cost. Thus, the effectiveness of QFD can be measured by the number of engineering changes made during product development, time cycle to the field, cost, and quality. Japanese companies, such as Toyota, have realized significant benefits in each of these areas. Using QFD, Toyota suppliers have reduced product development cycle time by thirty-three to fifty percent while improving quality and reducing costs by similar percentages (Sullivan, 1987b:1-4).

QFD is important to VRP in that it identifies the target values and critical parameters. Then, parameter design can be used to refine the target values during "Part Planning" and "Process Planning."

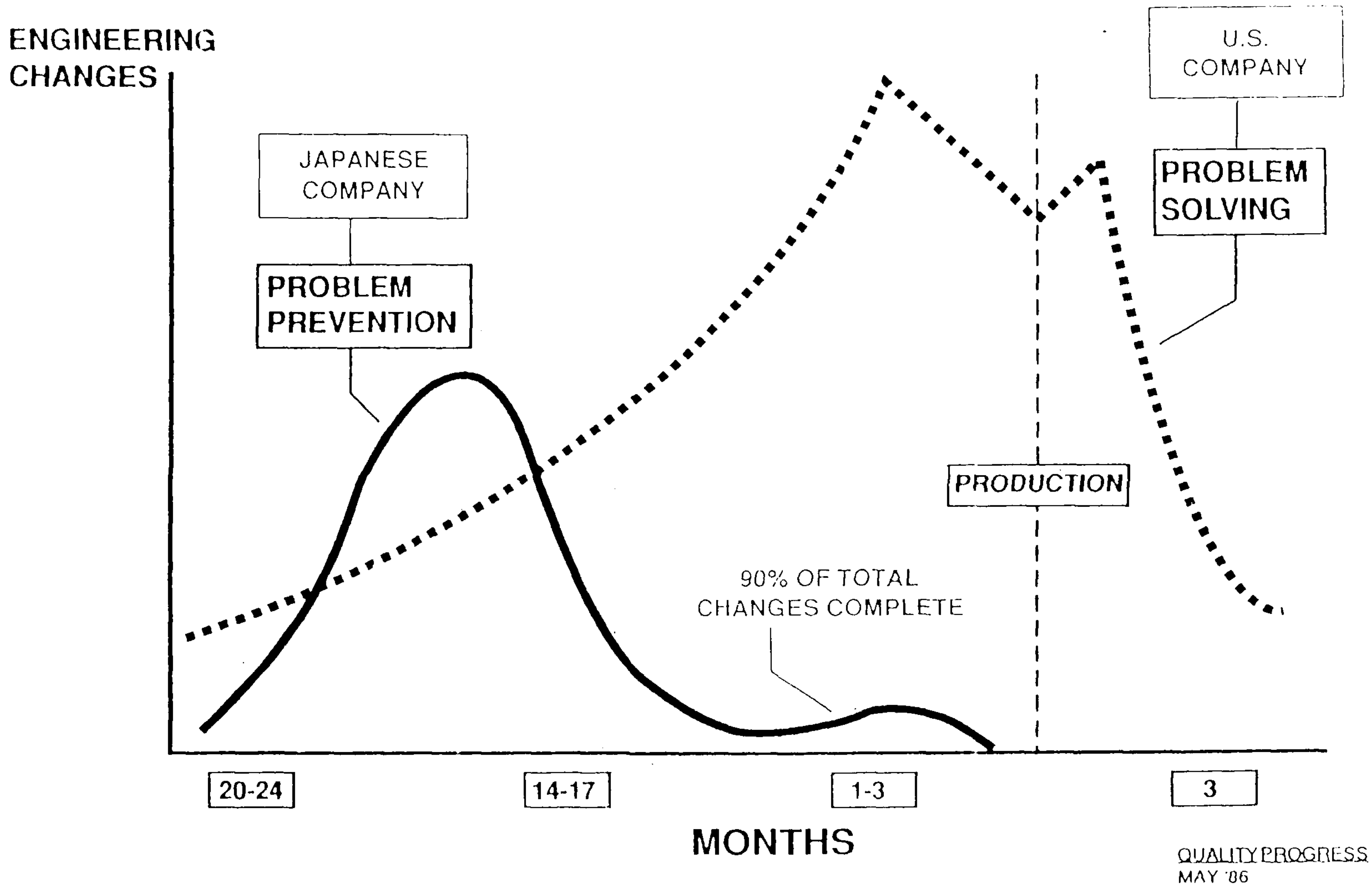


Figure 17. Comparison of Japanese and U.S. Engineering Changes

(Source: ASI, 1988:VII-11)

<u>Statistical Process Control</u> (SPC) is an on-line method for reducing variability in the manufacturing and assembling phases of production. SPC is the application of accepted statistical methods used to determine if a given process is within operating control limits. SPC determines if a process is statistically in control to produce a uniform defect-free product (McKee, 1985:Q6).

Quality assurance during production is primarily a function of statistical process control (Sullivan, 1986a:79). The control chart is the fundamental statistical tool for improving quality. A control chart is a graphic comparison of process performance data to computed control limits (Juran, 1980:288). The process performance data consist of chronological groups of data measurements obtained sequentially during production. The process performance data are then plotted on the control chart to detect assignable causes of variation.

Assignable variation differs from random variation in that random variation is uncontrollable--induced purely by chance. However, assignable variation caused by specific "findable" causes can often be controlled. Ideally, a process should only be subject to random variation because this represents the smallest amount of variation possible in an established process. A process that is operating without assignable causes of variation is in a state of "statistical process control" (Juran, 1980:289).

The primary advantage of the control chart is to discover variability. Once assignable variation has been identified, laborers, engineers, and management can alter the process to reduce variability.

Any process can be made to appear in statistical control by changing specifications but this is not the premise behind the concept. It is desirable to have some measurements outside the control limits because these points represent causes of variability. Assignable causes of variability are potential sources of process improvement.

The Shewhart rule specifies a process is in control when two thirds of the measurements fall within one third of the control limits with some measurements falling outside the control limits as illustrated in Figure 18. The next step is to change the process bringing all measurements inside the control limits. Once this is achieved, the limits should be redefined so that the process is always moving closer toward the target value. This continuously reduces variability by successive process improvements resulting from the narrowing of the control limits (Sullivan, 1986a:80). It is important to note that control limits are different than specification limits.

Design and manufacture as close to target values as possible, not just within the specification limits.

```
UPPER PROCESS LIMIT      ------------------------------- 3/3
                         :
                         :------------- --------------- 2/3
                         :       x         x
                         :----------------------x------ 1/3
                         :   x         x               x
TARGET VALUE             :-x-------x-----x-----x--------
                         :           x               x
                         :------------------------------ 1/3
                         :     x             x
                         :------------------------------ 2/3
                         :                         x
LOWER PROCESS LIMIT      ------.-----.-----.-----.-----. 3/3

        SAMPLE NUMBER          3     6     9     12    15
```

Figure 18. SPC Control Chart

Walter Shewhart developed the control chart in the early 1920's as an aid to identify potential problems in production before producing a defective product. The control chart allowed the worker to differentiate between random variation and assignable variation of a process. In the industrial environment, the worker is best situated to monitor the production process and discover assignable causes. However, management support is necessary to correct these causes (Reid, 1985:Q3).

Troubleshooting Techniques

A problem must first be identified before it can be corrected. Analytical studies are a prelude to corrective action on a process. However, prior to analytical study, the process must first be documented and defined.

A process is the transformation of inputs into outputs while adding or creating value in either time, place, or form.

> Time value: Something is available **when** it is needed.
> Place value: Something is available **where** it is needed.
> Form value: Something is available **how** (in the form in which) it is needed.

INPUTS		PROCESS		OUTPUTS
Manpower/Services		Transformation of inputs,		Manpower/Services
Equipment		value (time, place, form)		Equipment
Materials/Goods	--->	is added or created	--->	Materials/Goods
Methods				Methods
Environment				Environment

Figure 19. The Basic Process
(Source: Gitlow, 1989:39)

The three techniques used most often to understand, analyze, and prioritize problems are:

1. The Process Flowchart
2. Cause and Effect (Ishikawa/Fishbone) Diagram
3. Pareto Analysis

The Process Flowchart

A process flowchart is a pictorial summary documenting the flow of the various operations of a process by depicting sequential steps involved in the process and showing the interrelationships between the steps.

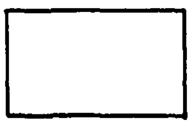
Flowchart Symbols

The American National Standards Institute, Inc. (ANSI) has approved the following set of flowchart symbols to document a process. Symbol shape and the information written within the symbol are useful in providing insight into a particular step of the process.

Basic Input/Output Symbol

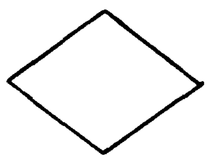
The general form that represents input or output media, operations, or processes is a parallelogram.

Basic Processing Symbol



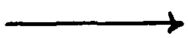
The general symbol used to depict a processing operation is a rectangle.

Decision Symbol



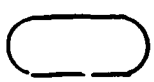
A diamond is the symbol that denotes a decision point in the process. This includes attribute type decisions such as pass-fail, yes-no. It also includes variable type decisions such as which of several categories a process measurement falls into.

Flowline Symbol



A line with an arrowhead is the symbol that shows the direction of the stages in a process. The flowline connects the elements of the system.

Start/Stop Symbol



The general symbol used to indicate the beginning and the end of a process is an oval.

Figure 20. Flowchart Symbols
(Source: Silver and Silver, 1986:142-147)

Guidelines for constructing Systems Type Flowcharts.

1. Draw the flow chart from the top of the page to the bottom and from left to right.

2. Carefully define and clarify the activity being flowcharted.

3. Determine where the activity starts and ends.

4. Describe each step of the activity using single-verb descriptions (e.g. design prototype)

5. Keep each step of the activity in its proper sequence.

6. Carefully observe the scope or range of the activity being flowcharted.

7. Use the standard (ANSI) flowcharting symbols. (Source: Fitzgerald and Fitzgerald, 1973:227-84).

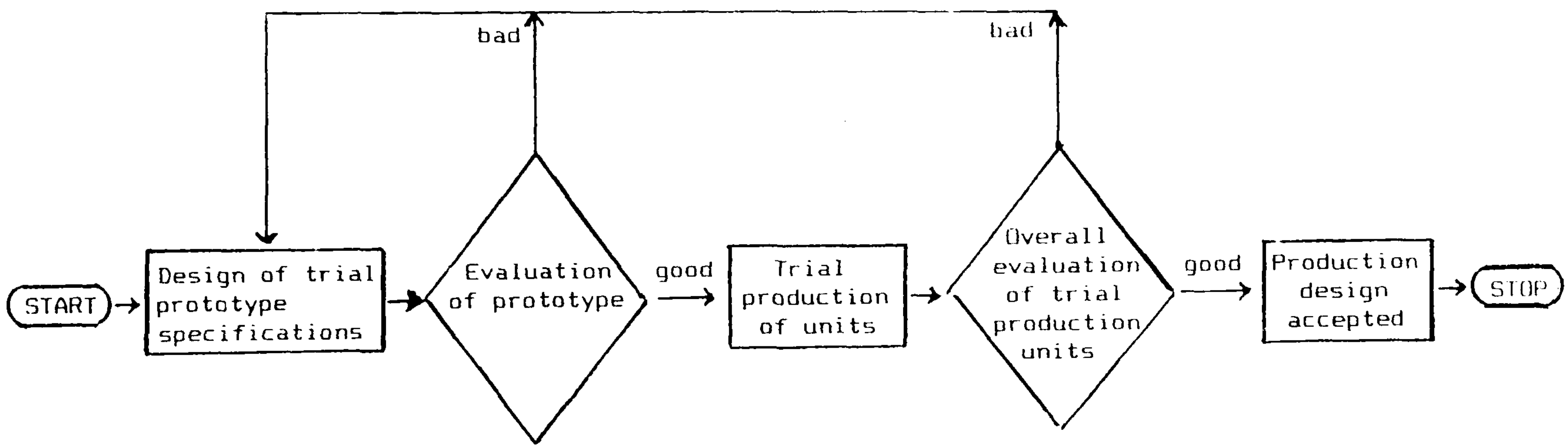


Figure 21. Quality of Design Study
(Source: Gitlow, 1989:43)

Cause and Effect Diagram

Cause and Effect analysis is used after brainstorming to organize the information produced in the brainstorming session. Analysis includes gathering and organizing possible reasons or causes of the problem, selecting the most probable cause, and verifying possible causes until a valid cause and effect relationship is established.

Also known as a Fishbone or Ishikawa Diagram, the cause and effect diagram depicts the linkage between the causal factors and the problem. The purpose of using a cause and effect diagram is to understand the factors affecting a process.

The following steps are recommended for creating a Cause and Effect Diagram.

1. Clearly define and state the problem. After the problem has been clearly defined, write it on the right side of a flip chart and draw an arrow to it.

----------------------> $\boxed{\text{Problem}}$

2. Identify major causes. A common method of determining the major causes is to consider the impact of machines, methods, material, manpower, and the environment on the problem.

3. Brainstorm sub-causes to uncover all of the possible sub-causes that contribute to the problem being studied and record the sub-causes on the diagram. It is important to note that only causes of the problem should be discussed at this point--not solutions.

4. Allow time to ponder the causes before evaluating them. Also consider interactions among the causes.

5. On the Cause and Effect Diagram, circle the likely causes of the problem under study.

6. Verify the most likely cause of the problem under study by collecting and analyzing data to ascertain if it has a significant impact on the problem. If the most likely cause does not have a significant impact on the problem, the group should then verify the next most likely choice to determine its impact on the problem, and so on until a viable solution to the problem is discovered (Gitlow,1989:382-385).

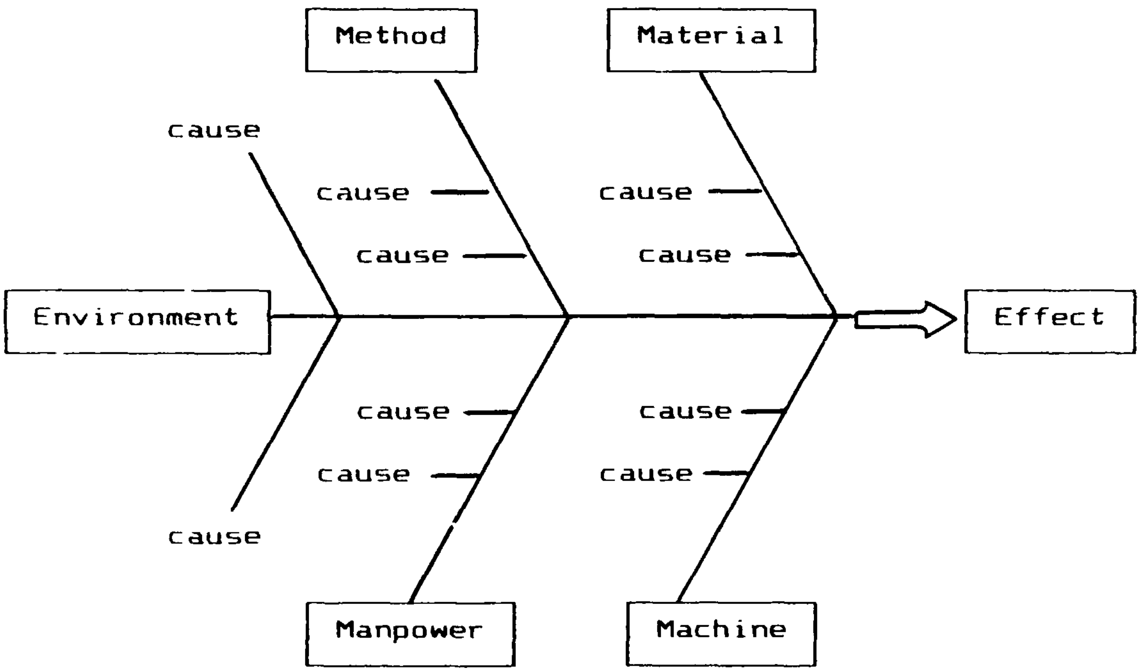


Figure 22. Generic Cause and Effect Diagram

Pareto Analysis

Pareto Analysis is a tool used to identify and prioritize problems. Vilfredo Pareto, a 19th century Italian economist, originated the concept of "the vital few versus the trivial many." The vital few are the few factors that account for the largest part (percentage) of the total. The trivial many account for the rest. From the Pareto concept, Lakelin formulated the 80-20 rule which states that approximately 80 percent of the value, costs, or problems come from 20 percent of the elements.

The Pareto diagram is a simple bar chart with the bars representing the frequency of each problem arranged in descending order so that the tallest bars are on the left side of the chart and descend to the right.

While Pareto analysis is commonly viewed as a problem solving tool, its primary use is in determining what problems to solve rather than how to solve them. (Ishikawa, 1976:43).

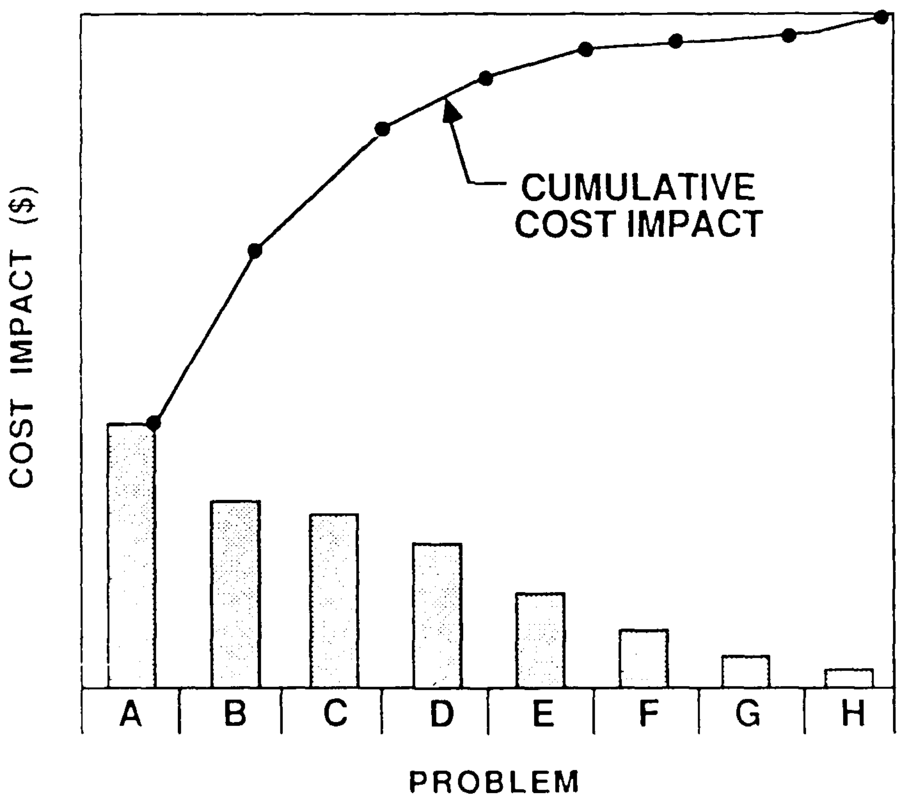


Figure 23. Pareto Diagram
(Source: VRP, 1989:B17-b)

Guidelines for constructing a Pareto Diagram:

1. Establish categories for the data being analyzed--classifying data according to defects, products, work groups, size, and other appropriate categories.

2. Specify the time period during which data will be collected. Three important considerations in establishing a time period to study are:

   a. a convenient time (i.e. one hour, one day, one week, one month, etc.).
   b. a constant time period for all related diagrams to make comparisons meaningful.
   c. time period should be relevant to the analysis.

3. Construct a frequency table arranging the categories from the one with the largest number of observations to the one with smallest number of observations. The frequency table should include a:

   a. category column;
   b. frequency column (indicates the number of observations per category with a total at the bottom of the column);
   c. cumulative frequency column (indicates the number of observations in a particular category including all frequencies in categories above it);
   d. relative frequency column (indicates the percentage of observations within each category with a total at the bottom of the column;
   e. relative cumulative frequency column (indicates the cumulative percentage of observations);

4. Construct the Pareto Diagram.

   a. Draw horizontal and vertical axes on graph paper.
   b. Mark vertical axis with the appropriate units starting at zero continuing up through the total number of observations in the frequency table.
   c. Under the horizontal axis, write the most frequently occurring category on the far left hand side with the next most frequently occurring category immediately to its right, and so on continuing in decreasing order.
   d. Draw in bars for each category.
   e. Plot a cumulative line indicating a cumulative percent scale on the right side of the chart. This is done by starting in the lower left hand corner and progressing diagonally to the top right corner of the first column.
   f. Title the diagram and briefly describe its data sources. (Source: Ishikawa, 1983:43-44)

Appendix C: Glossary of Terms

Cause and Effect Analysis: used after brainstorming session to construct a cause and effect diagram showing the linkage between causal factors and the problem.

Control Factor: Factors whose values can be selected and controlled by the experimenter such as materials and processing.

Design of Experiments: technique used to identify critical parameters, isolate the causes of variation, and to improve technical or operational characteristics enhancing quality and fitness for use.

Environmental Factors: surroundings and conditions the product will operate in.

Manufacturing Variations: manufacturing conditions causing product production to deviate from its nominal values.

Noise: Any uncontrollable factor causing a product's performance characteristics to deviate from nominal values or cause a deterioration in actual performance when compared to desired performance.

Parameter Design: The design stage where product or process parameter values are determined establishing critical dimensions and characteristics to "optimize" performance with minimum sensitivity to noise.

Pareto Diagram: bar chart where bars represent the frequency of each problem and are arranged in descending order; primary use is in determining problems rather than solving them.

Process Flowchart: pictorial summary documenting the flow of various operations of a process by depicting sequential steps involved in the process and showing the interrelationships between the steps.

Product Deterioration: changes in product parameters occurring over time due to wear and tear on the product.

Quality Function Deployment: off-line variability reduction methodology for translating users' requirements into product and process characteristics.

Quality Characteristic: determines how quality is measured in terms of nominal is best, smaller is better, larger is better, attribute, or dynamic.

Quality Loss Function: Parabolic approximation representing the value lost when a quality characteristic deviates from its best (or target) value.

Robustness: Condition of a process/product design indicating insensitivity to noise so that a product functions with limited variability when operated under any operating condition.

Statistical Process Control: on-line method for reducing variability in the manufacturing and assembling phases of production.

System Design: The initial engineering effort where the design concept is defined.

Tolerance Design: the process of specifying tolerances and the nominal settings defined during the parameter design stage.

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The focus of this study is on Variability Reduction (VR). Specifically, this thesis reviews Air Force policy regarding Variability Reduction, examines Variability Reduction's role in the Department of Defense's Total Quality Management (TQM) initiative including the United States Air Force Reliability and Maintainability 2000 (USAF R&M 2000) Process, and addresses several Variability Reduction methods. The primary objective of the research was to produce a Variability Reduction Process Handbook explaining several of the concepts involved in Variability Reduction, thus providing Air Force managers a better understanding of Variability Reduction methodologies. Additionally, the handbook emphasizes the importance of implementing this aspect of quality.

Variability Reduction methods can be applied to selected phases within a system's life cycle and are essential to integrating two seemingly incompatible goals--fielding highly reliable and maintainable, combat capable systems while decreasing development time and reducing production and operational costs. Variability Reduction stresses uniformity around a target value rather than conformance to specification limits. Robust designs make products insensitive to noise, thus improving performance and enhancing reliability.